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SUB-TERAHERTZ RANGE FIBER OPTIC DEVICES FOR
SENSING APPLICATIONS

BY

ZHEN CHEN

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN

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2017

DOCTOR OF PHILOSOPHY DISSERTATION

OF

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UNIVERSITY OF RHODE ISLAND

2017

ABSTRACT

Distributed sensing refers to the solution which enables the real-time, continuous measurement at multiple sensing locations (typically, more than 100 sensing nodes). Due to many of its unique advantages, such as small size, light weight, low cost, electromagnetic immunity, high-temperature survivability, and chemical stability, optical fibers have been well accepted as one of the most promising candidates as the platform for distributed sensing applications.

Among different fiber distributed sensing methods, optical frequency domain reflectometry (OFDR) represents a particular promising candidate. Based on the frequency modulated continuous wave (FMCW) method, OFDR method is capable of measuring the spatial-continuous weak Rayleigh scattering patterns along the entire length of the fiber under test, with high spatial resolution ($\sim\mu\text{m}$) level and moderate interrogation distance ($\sim\text{km}$). To extract the structural information from the unmodified communication grade single mode fiber, large interrogation bandwidth is needed. However, this resource of optical bandwidth is very expensive. The external cavity laser is the state-of-the-art frequency sweep laser source for OFDR system, which costs at least \$ 20,000. The cost has rendered the OFDR interrogation technique expensive and limits its applications.

This dissertation focused on the improvement of OFDR interrogation system by reducing the total system cost. First, a series of sub-terahertz range fiber sensors, including Fabry-Perot cavity sensors and terahertz fiber grating sensors were symmetrically investigated. Fabricated using femtosecond laser micromachining techniques, these sensors allow the OFDR system for low bandwidth interrogation while

maintaining the high accuracy measurement. In addition, a sensor fabrication method without stripping the fiber polymer buffer was developed. This is the first time that an in-line grating structure has been fabricated within the core of an optical fiber with an intact buffer coating, allowing the fiber to retain optimal mechanical properties.

Second, a series of low cost sweep laser sources were developed as high-linear coherent sweep laser source, suitable for the sub-terahertz range fiber sensor interrogation. Based on current injection modulation methods, the semiconductor lasers were used as the sweep laser sources and the output wavelength was feedback controlled using optical phase locked loop techniques. The method of using VCSEL laser was also investigated to increase the sweep bandwidth. In addition, an all-digital optical phase locked loop system was implemented using the field programmable gate array, which increases the system design flexibility.

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PREFACE

This dissertation is organized in the manuscript format consisting of eight manuscripts as following:

- Manuscript 1:

Z. Chen, L. Yuan, G. Hefferman and T. Wei, “Ultra-weak intrinsic FP cavity array for distributed sensing”, published in *Optics Letters*, vol.40, no.3, pp.320-323, Feb. 2015.

- Manuscript 2:

Z. Chen, L. Yuan, G. Hefferman and T. Wei, “Terahertz fiber Bragg grating for distributed sensing”, published in *Photonics Technology Letters, IEEE*, vol. 27, no. 10, pp. 1084 - 1087, May. 2015.

- Manuscript 3:

Z. Chen, G. Hefferman, L. Yuan, Y. Song and T. Wei, “Ultra-weak waveguide modification with femtosecond laser pulses”, published in *Photonics Technology Letters, IEEE*, vol. 27, no. 16, pp. 1705 - 1708, Jun. 2015.

- Manuscript 4:

G. Hefferman, Z. Chen and T. Wei, “Phase-shifted terahertz fiber Bragg grating for strain sensing with large dynamic range”, published in *Photonics Technology Letters, IEEE*, vol. 27, no. 15, pp. 1649 - 1652, Jun. 2015.

- Manuscript 5:

Z. Chen, G. Hefferman, L. Yuan, Y. Song and T. Wei, “Terahertz-range interrogated grating-based two-axis optical fiber inclinometer”, published in *Optical Engineering, SPIE*, vol. 55, no. 2, pp. 026106, Feb. 2016.

- Manuscript 6:

Z. Chen, G. Hefferman and T. Wei, “A low bandwidth DFB laser-based interrogator for terahertz-range fiber Bragg grating sensors”, published in *Photonics Technology Letters, IEEE*, vol. 29, no. 4, pp. 365 - 368, Feb. 2017.

- Manuscript 7:

Z. Chen, G. Hefferman and T. Wei, “Digitally controlled chirped pulse laser for sub-terahertz-range fiber structure interrogation”, published in *Optics Letters*, vol. 42, no. 5, pp. 1007-1010, Mar. 2017

- Manuscript 8:

Z. Chen, G. Hefferman and T. Wei, “Field-programmable gate array-controlled sweep velocity-locked laser pulse generator”, published in *Optical Engineering, SPIE*, vol. 56, no. 5, pp. 054102, May. 2017.

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MANUSCRIPT

1. Ultraweak intrinsic Fabry–Perot cavity array for distributed sensing

by

Zhen Chen, Lei Yuan, Gerald Heffernan and Tao Wei

published in

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Abstract

This Letter reports on an ultraweak intrinsic Fabry–Perot interferometer (IFPI) array fabricated by a femtosecond (fs) laser for distributed sensing applications. Ultralow reflectors (< -60 dB) were obtained. IFPIs with different physical lengths showed identical temperature sensitivity (-1.5 GHz/°C). A distributed temperature sensing test was conducted. No crosstalk between IFPI elements in the array was observed, implying the device's utility as a distributed sensing system. The possibility of using smaller bandwidths for sensor interrogation was experimentally proven. A small-scale temperature distribution test was conducted on a continuously cascaded ultraweak IFPI array, demonstrating its high spatial resolution. The temperature detection limit of this system was measured to be less than 0.0667°C .

Introduction

Distributed optical fiber sensing technology is a thriving branch of sensing technology, due in large part to its ability to surmount many limitations of traditional single-point sensor, enabling a single system to simultaneously span a large number of equivalently individual sensors [1]. These unique advantages have been successfully demonstrated in many application areas, including oil drilling, structural health monitoring, and perimeter security [2]. The recent development of distributed optical fiber sensors with high spatial resolution has expanded this utility considerably, making it an attractive addition to many emerging applications, such as wearable devices, robotics, and surgical instrument [3, 4].

The use of Rayleigh scattering as a sensing method has shown particular promise in distributed sensing with high spatial resolution [5]. The unique Rayleigh

backscattering profile of a section of optical fiber can be extracted via swept-frequency interferometry, revealing the profile of ambient temperature and strain change along the length of the fiber. By sweeping over a broad optical bandwidth, this technology can resolve minute changes in Rayleigh backscattering profile with mm-level spatial resolution. However, this modality requires the interrogating laser to sweep over a broad wavelength range with high coherence length, limiting the update rate of the measurement system. Additionally, broadband, highly coherent, and single longitudinal mode swept lasers come at considerable cost.

Weak fiber Bragg grating (FBG) arrays represent another technology breakthrough in this area [6]. A large number of low reflection FBGs with same nominal resonant wavelength are fabricated along an optical fiber in a discrete fashion, known as weak FBG sensor network, or in a continuous fashion, known as long-length FBG [7]. The sensing mechanism of an individual weak FBG is the same conventional FBG; however, in contrast to the wavelength domain multiplexing (WDM) technology used for traditional FBGs, a weak FBG array is multiplexed in the spatial domain. The low reflectivity of each individual FBG element ensures minimal crosstalk among FBGs in an array. Researchers have demonstrated several probing technologies to interrogate weak FBG arrays, including combined wavelength-time-domain reflectometry, optical frequency domain reflectometry (OFDR), and synthesis of optical coherence function (SOCF) method [7]. The responses of thousands of individual weak FBGs in a single array can be measured simultaneously. In comparison with the Rayleigh scattering approach, weak FBGs require a significantly smaller wavelength range for sensor

interrogation, leading to a higher update rate. Currently, a weak FBG array is fabricated during the fiber drawing process and features a reflectivity of ~ -33 dB [8].

There exists another highly sensitive, miniature-scale, and low reflection device in the optical fiber sensor family – intrinsic Fabry–Pérot interferometer (IFPI). This technology uses a pair of small reflectors introduced in an optical fiber, forming a cavity that creates interferogram in the wavelength domain. Ambient physical changes are detected through shifts of the resulting interferogram. Traditionally, the reflectors of IFPIs are fabricated via splicing together different optical fibers of differing refractive indices or via exposing a fiber to intense UV light [9]. Recent technology advances have led to increased popularity in the use of femtosecond (fs) lasers in fabricating fiber optic devices [10, 11]. Weak reflectors with a reflectivity of ~ -45 dB were achieved to form IFPIs with this fabrication method [12]. An FFT-based method was used to multiplex 3 IFPIs of differing cavity lengths. Very recently, Huang et al. successfully demonstrated an optical carrier based microwave interferometry method to simultaneously interrogate identical and cascaded IFPIs with a length of 12 cm along an optical fiber [13]. However, the low microwave frequency bandwidth limits its spatial resolution.

This letter reports a fiber-inline ultra-weak (< -60 dB) IFPI array fabricated using fs laser for distributed sensing with high spatial resolution. Interrogation approach, fabrication parameters, sensitivity, operation bandwidth, and distributed sensing ability of the proposed IFPI array were experimentally investigated in this letter.

Figure 1.1 Schematic of the interrogation system for IFPI arrays

Operation Mechanism

The Schematic of the interrogation system, based on OFDR, is drawn in Figure 1.1. Light from a tunable laser source (TLS, Newport 6428) is split into two paths – “clock” and “signal”. “Clock” is an interferometer used to calibrate the non-linear sweep effect of the TLS by providing a corrected time base for a data acquisition card (DAQ, NI 6251 with the sampling rate of 1MHz) during frequency sweep. Light in the “signal” section is split between the reference and measurement arms of an interferometer via a 50/50 coupler (CPL); in the measurement path, an optical circulator (CIR) further splits the light to interrogate the low-reflection IFPI array and returns the reflected light. A polarization controller (PC) is used to tune the state of polarization in the system. Another 50/50 CPL then recombines the measurement and reference fields. In this setup, the TLS sweeps from 1535 to 1565 nm at a speed of 16 nm/s, covering a total bandwidth of 3.7 THz. Thus, the AC-coupled voltage received by the DAQ is written as:

$$v_{total} = 2 \eta r I_{ref} \sum_{n=1}^{N-1} \cos[\beta(Z_{ref} - Z_n)]$$

where η is the light-to-voltage conversion coefficient of the photodetector, r is the reflection coefficient of the reflector of the IFPI, I_{ref} is the light intensity of the reference

arm, N is the number of reflectors along the optical fiber, β is the propagation constant, z_{ref} is the length of reference fiber, and z_n represents the position of n th reflector. The intensity of the reflected light as a function of position can be readily obtained via a Fourier transform. It is worth noting that Rayleigh backscatter in this system is considered as noise floor in this study. Two neighboring reflectors form an IFPI, which can be time-gated and extracted via a digital band-pass filter. The real-time system samples at 3 seconds per round. The data collected by DAQ is transmitted and processed on computer.

Figure 1.2 Microscopic image and reflection distribution in spatial domain of three 1 cm IFPI cavities fabricated using differing laser power: (a) 0.14, (b) 0.12, and (c) 0.1 W.

A Ti: Sapphire fs laser (Coherent, Inc.) micromachining system was used to fabricate ultra-weak reflectors. The central wavelength, pulse width, repetition rate, and maximum power of the laser are 800 nm, 200 fs, 250 kHz, and 1 W, respectively. The actual power used for fabrication is controlled by adjusting a half-wave plate, a

polarizer, and several neutral density (ND) filters. The laser was switched on or off by electrically gating the internal clock. A single-mode optical fiber (Corning, SMF-28e) with the core and cladding diameters of 8.2 and 125 μm , respectively, was used for these experimental trials. After mechanically stripping its buffer, the fiber was cleaned using acetone and clamped onto two bare fiber holders, which were immersed in distilled water during fabrication. The fiber assembly was mounted on a computer-controlled three-axis translation stage with a resolution of 0.1 μm (Newport, Inc.). The fs laser beam was focused inside the optical fiber through a water immersion objective lens (Olympus UMPlanFL 20x) with a numerical aperture (NA) of 0.4. The velocities of the stages were set at 50 $\mu\text{m/s}$ during fabrication. A cuboid region ($10 \times 2 \times 10 \mu\text{m}$) was inscribed in the center of the fiber from bottom up to cover the whole cross-section of the fiber core. The center of the inscribed region was aligned with the center of the fiber core. Figure 1.2 shows both the microscopic images and reflection distribution of three IFPIs fabricated with different fs laser powers (0.14, 0.12, and 0.1 W). The reflection values measured using the interrogation system were referenced to an angled polished connector (APC), which was previously measured using off-the-shelf precision instruments. The reflectivity of the weak reflectors decreased as fabrication power was reduced. A reflectivity of around -70 dB was achieved with laser beam at 0.1 W. In this study, 0.14 W was chosen as the fs laser power used for IFPI fabrication.

The sensing mechanism of an IFPI is based on tracking the phase shift of the interferogram in response to ambient change. To extract the phase shift information from the signal received from an individual IFPI, the reflection signal in frequency-

domain is squared and filtered using a low-pass filter to obtain the interference signal (S):

$$S = 4\eta^2 r^2 I_{ref}^2 \cos(4\pi n_{eff} L_f / c)$$

where L is the physical cavity length of IFPI, n_{eff} is the effective refractive index of the fiber, f is the frequency of the laser, and c is the velocity of light in vacuum. Additionally, $n_{eff}L$ is considered the optical length of the IFPI cavity. From Equation (2), as optical length increases, the period of the cosine function with respect to laser frequency decreases. As a result, at laser frequencies (~ 193 THz), the interference signal shifts to smaller frequencies, proportionally.

To investigate ultra-weak IFPI sensors, two IFPIs with lengths of 1 cm and 1 mm, respectively, were fabricated. The temperature response of both IFPIs was measured using a temperature-controlled water bath. Figure 1.3 (a) and 1.3(b) plot the measured interferogram of both IFPIs at 63°C and 65°C, where the x-axis is the frequency offset from the start of frequency sweep. As temperature increases, the optical length of both IFPIs increases, leading to an interferogram shift towards lower frequency. The frequency shift of interferogram is determined via tracking its zero-crossing position. This technique is justified by the fact that steepest slope of a sinusoidal function occurs at its zero-crossing position. Figure 1.3(c) depicts the frequency shift of the interferogram as a function of temperature for both IFPIs. The temperature sensitivity of both 1 cm and 1 mm IFPIs was measured to be around -1.5 GHz/ °C, agreeing well with the theory value [12]. Comparing the two IFPIs, the interference period with respect to frequency for the 1 cm IFPI is 1/10 of the 1 mm IFPI. As a result, the 1 cm IFPI is more subject to 2π ambiguity problem, limiting its measurement dynamic range.

However, the slope of the 1 cm IFPI at zero-crossing position is ten times higher than that of the 1 mm IFPI, leading to a much higher accuracy. As a result, an IFPI with a longer length is suitable for precisely measuring smaller physical changes.

Figure 1.3 Temperature responses of IFPIs of differing lengths: (a) interferogram of a 1 cm IFPI at 63°C and 65°C; (b) interferogram of a 1 mm IFPI at 63°C and 65°C; and (c) frequency shifts as a function of temperature for both 1 cm and 1 mm IFPIs.

Experimental Results and Discussions

To demonstrate the distributed sensing capability of ultra-weak IFPIs, three identical 1 cm IFPIs were fabricated and spliced along a single fiber line. Figure 1.4 (a) depicts the reflection distributions of the 3 ultra-weak-IFPIs, which were spaced approximately 1.5 m apart. The 2nd IFPI (middle) was immersed in a temperature-controlled water bath, while the 1st and 3rd IFPIs were left unchanged at ambient temperature. The water bath was heated to 65°C and cooled down to 63°C. Three bandpass filters were used to gate the 3 IFPIs in time-domain and extract the interferograms of all 3 IFPIs in frequency-domain, shown in Figure 1.4 (b)-(d). As expected, the interferogram of the 2nd IFPI shifted to higher frequencies as temperature decreased. Concurrently, the 1st and 3rd interferogram remained unchanged. No

crosstalk was observed between IFPIs in this experiment, indicating that this technology holds considerable potential for distributed sensing applications.

Figure 1.4. Demonstration of ultra-weak IFPIs for distributed sensing, where only the 2nd IFPI is subject to temperature change: (a) reflection distributions of 3 IFPIs; (b) interferogram of 1st IFPI when ambient temperature of 2nd IFPI is varied; (c) interferogram of 2nd IFPI at 63°C and 65°C; (d) interferogram of 3rd IFPI when temperature of 2nd IFPI is varied.

A key advantage of an IFPI array over the Rayleigh scattering method is that an IFPI does not require a large bandwidth to resolve small changes with high spatial resolution. To demonstrate this feature, a 1 cm IFPI was experimentally tested using different laser sweeping bandwidths. Figures 5(a)-(c) depict the interferograms of the IFPI at 63°C and 65°C with 3 laser sweeping bandwidths. It can be observed that the interferograms generated using these different interrogation bandwidths are similar. The identical temperature response with different sweeping bandwidths, shown in Figure 1.5 (d), further confirms IFPI's capability to operate within relatively narrow bandwidths.

Figure 1.5 Temperature response of a 1 cm IFPI interrogated using different laser sweeping ranges: (a)-(c) interferogram of the IFPI (d) temperature response with 3 interrogation bandwidths.

To investigate the spatial resolution of the proposed technology, an IFPI array was fabricated along the fiber in a continuous fashion with identical individual cavity length to be 1 cm. The reflection distribution of this array is depicted in Figure 1.6(b), which spans 5 cm. The reflectivity of reflectors in this array is around -60 dB. The interferograms of all 5 IFPIs were first measured as a reference. Then, a cube of ice was placed ~ 1 cm away from the center of the IFPI array as sketched in in Figure 1.6 (a). The interferograms were again taken, and the frequency shifts as a function of IFPI location plotted in Figure 1.6 (c). A Gaussian-like temperature distribution was observed, in which the center IFPI experienced a temperature around 1°C lower than IFPIs at either edge as expected. This experiment proves that continuously cascaded IFPIs can be used for distributed sensing. The spatial resolution is the cavity length of the individual IFPIs, i.e., 1 cm in this test.

Figure 1.6 Experimental study of continuously cascaded ultra-weak IFPIs: (a) test setup; (b) reflection distribution of 5 IFPIs; (c) frequency distribution measured using IFPI array.

To evaluate system-level accuracy, a stability test was conducted by fixing the ambient condition of a 1 cm IFPI. 100 groups of interferogram were generated using this device. The frequency shift of each interferogram relative to its initial status was calculated. The standard deviation of the frequency shift is less than 100 MHz, determining the system's detection limit. Given the experimentally measured sensitivity of $-1.5 \text{ GHz/}^{\circ}\text{C}$, its temperature detection limit is calculated to be less than 0.067°C .

Previous studies of weak FBG sensors suggest that the multiplexing capacity is mainly limited by two types of crosstalk [6]. The first is spectral shadowing—spectral distortion of the downstream devices caused by the insertion loss of the upstream devices; the second is multiple-reflection crosstalk, or the spectral distortion induced by false signals, which undergo multiple reflections between upstream devices, and experiences the same time delay as the real signal. Both types of crosstalk are exponentially proportional to the reflectivity of the device. Ideally, the reflectivity of an IFPI is calculated by doubling the reflectivity of a single reflector. The smallest reflector achieved in our lab was -72 dB , converted to a -69 dB IFPI, which is more than 30 dB

smaller than the current ultraweak FBGs. A theoretical model was applied to estimate the multiplexing capacity of the proposed ultraweak IFPI sensor array [6]. The spectral shadowing effect was simulated in a sensor array of 100,000 IFPIs. In this model, the frequency shifts of all upstream sensors can maximally contribute an unwanted spectral shift of 63.64 MHz to the last IFPI, converted to a reasonable temperature measurement uncertainty of 0.042°C. In addition, when multiple-reflection crosstalk is considered as the only noise source, a total multiplexing number of 1 million maintains a signal-to-noise ratio (SNR) of 20 dB, indicating its negligible influence. To summarize, 100,000 is approximated as the system's multiplexing capacity. In practice, this number will decrease due to the coherence length limit, total length of fiber, detector quality, and unwanted extra loss along the fiber. Nevertheless, the proposed ultraweak IFPI array technology holds considerable potential to increase the multiplexing capacity by orders of magnitude beyond current methods.

Conclusions

To conclude, we reported an ultra-weak IFPI array fabricated by fs laser for distributed sensing applications. Reflectivity of weak reflectors decreases as the fs laser power is reduced. IFPI cavities with different physical lengths (1 cm and 1 mm) showed identical temperature sensitivity ($-1.5 \text{ GHz}/^\circ\text{C}$). A distributed temperature sensing test was conducted and no crosstalk between IFPI elements observed, implying utility as a distributed sensing system. The system was experimentally proven to be capable of operating within a small bandwidth. A small-scale temperature distribution test was conducted on a continuously cascaded ultra-weak IFPI array, demonstrating its high

spatial resolution. The temperature detection limit of this system was measured to be less than 0.0667 °C.

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MANUSCRIPT

2. Terahertz fiber Bragg grating for distributed sensing

by

Zhen Chen, Lei Yuan, Gerald Heffernan and Tao Wei

published in

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Abstract

This letter reports a fiber Bragg grating for distributed sensing applications fabricated using single-mode optical fiber and a femtosecond laser and interrogated in the terahertz range. A theoretical model of device behavior was derived, which agreed well with experimentally observed device behavior. In order to investigate the utility of terahertz fiber Bragg gratings (THz FBGs) as a sensing modality, temperature tests were conducted. The results demonstrated a sensitivity of $-1.32 \text{ GHz/}^{\circ}\text{C}$ and a detection limit of less than $0.0017 \text{ }^{\circ}\text{C}$. A temperature distribution test was also conducted using a THz FBG, demonstrating its potential as a distributed sensing platform with high spatial resolution. The feasibility of interrogating THz FBGs using narrow interrogation bandwidths was also experimentally shown.

Introduction

The Bragg grating is a mature sensing technique that has been widely used for strain, stress, pressure, and temperature measurement. Through the integration of these periodic structures into a variety of waveguides, the utility of Bragg grating technology has been successfully demonstrated over a broad set of frequency ranges. In the optics domain, incident frequencies in the hundreds of terahertz are routinely used to interrogate fiber Bragg gratings (FBG) [14]. By resolving shifts in the reflected spectra, subtle changes in the parameters of interest can be precisely measured. Similar utility has been demonstrated in the microwave domain (a few gigahertz) through the successful implementation of coaxial cable Bragg gratings (CCBG) fabricated by introducing discontinuities at the centimeter scale [15, 16].

Both FBG and CCBG have demonstrated their utility for large scale, multiplexed sensing applications [6, 17]. However, these techniques have distinct limitations; the large frequency ranges necessary for interrogation in the optical domain require swept frequency lasers, or a combination of broadband light source and optical spectrum analyzer, with broad ranges (tens of nm, or a few terahertz, at a wavelength of around 1550 nm) [18], while the long pitch-length of CCBGs in the microwave domain limits its spatial resolution (~tens of cm) for sensing applications.

Terahertz frequency sensing has emerged as a promising method of surmounting the limitations of both the optical and microwave domains. Terahertz frequencies lie between the optical and microwave frequency ranges, which are hundreds of terahertz and tens of gigahertz, respectively. As a consequence of this spectral position, terahertz sensing has the potential to marry the positive qualities of both optical and microwave Bragg grating techniques [19]; as compared to a FBG and CCBG, THz gratings require a narrower interrogation bandwidth (hundreds of gigahertz) and have greater spatial resolution (pitch length < 1 mm), respectively.

This possibility has led to recent promising experimental investigation. Zhou et al., using a KrF laser to modify Topas polymer fiber, interrogated the resulting structure using a high frequency vector network analyzer at hundreds of gigahertz [20]. Similarly, Yan et al. used a CO₂ laser to modify a step-index polymer fiber, testing the structure using terahertz time-domain spectroscopy at hundreds of gigahertz [21]. Both methods, however, suffer from significant insertion loss as a result of large perturbations of the waveguides, which significantly limits the multiplexing capability of resulting sensors. Additionally, the need to interrogate these sensors using direct terahertz frequency

modulation requires the use of precision instrumentation at considerable expense due to the high attenuation of the interrogating circuit at THz frequencies.

In this letter, we report a terahertz fiber Bragg grating (THz FBG) sensing modality with the potential to overcome these engineering limitations. By using heterodyne mixing, a mainstay of microwave photonics, this technique has the potential to lead to both simplified sensor interrogation using narrow interrogation bandwidths and greatly-enhanced distributed sensing capacity with high spatial resolution [1, 13, 22, 23]. The interrogation system, fabrication parameters, and sensing utility of THz FBGs were experimentally studied, and the results presented in this letter.

Operation Mechanism

Figure 2.1 Schematic of the interrogation system for THz FBG

The schematic of the interrogation system, based on optical frequency domain reflectometry (OFDR), is shown in Figure 2.1 [24, 25]. The light generated by the tunable laser source (TLS) is split by a 90/10 optical coupler (CPL) into two paths, “clock” and “signal”. The “clock” path with two 50/50 CPLs is an interferometer that provides the sample clock for the data acquisition card (DAQ), compensating for the non-linearity of the tunable laser. The sampling rate of DAQ is 14 MSa/sec. The light in the “signal” path is split using a 50/50 coupler into a reference arm and a detection arm; a circulator (CIR) guides the reflected light from the THz FBG structure, which is

terminated with anti-reflected cut; a polarization controller is placed on the reference arm to adjust the interferometer for maximum output; another 50/50 CPL recombines the light from reference arm and detection arm to the balanced photodiodes (BPD) and DAQ. In this setup, the tunable laser sweeps from 1525 to 1555 nm at 60 nm/s scanning speed, corresponding to a total bandwidth of 3.8 THz, resulting in 1066357 sampling points in one waveform. The bandwidth of the tunable laser was reduced to 40 GHz to demonstrate the possibility of using smaller bandwidth for sensor demodulation. The real-time system has an update rate of 1.5 sec per round, which includes 0.5 sec for laser scanning and 1 sec for transmission of the data to a PC and calculation. The coherence length of the tunable laser is around 400 m, limiting the total length of the fiber detection arm to be 400 m.

Figure 2.2 Fabrication of THz FBG with femtosecond laser

Figure 2.2 illustrates the technique used to fabricate the THz FBGs under experimental investigation. The structures were fabricated with a Ti:Sapphire fs laser (Coherent, Inc.) micromachining system from the single-mode optical fiber (Corning, SFM-28), with core and cladding diameters of 8.2 and 125 μm respectively, for all experimental trials [10, 11, 26]. The insertion of each reflector is smaller than 0.001 dB.

Figure 2.3 Simulation and experimental results: (a) 1 mm, 20 reflection points, 0.11 W; (b) 0.1 mm, 20 reflection points, 0.11 W

A theoretical framework was developed to model the behavior of a multiplexed THz FBG. In this model, M same THz FBGs are embedded along the detection arm, with each FBG containing equally N reflection points with a period of Δz . The total AC coupled voltage received by the DAQ can then be expressed as:

$$v_{total} = 2\eta r I_{ref} \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} \cos[\beta(z_{ref} - z_m - 2n\Delta z)]$$

where η is the light-to-voltage conversion coefficient of the photodiode, r is the reflection coefficient of the FBG reflectors, I_{ref} is the light intensity of the reference arm, β is the propagation constant, z_{ref} is the length from the reference arm to the PD, and z_m is the length from the start of the m^{th} FBG to the PD. The intensity of the reflected light can be obtained using a Fourier transform. In this study, Rayleigh scattering is defined as the noise floor, resulting in a signal-to-noise ratio (SNR) of ~ 23 dB. Signal from target FBGs from the fiber under test can be extracted via a Butterworth band-pass filter. The sensing mechanism is based on tracking the frequency shift of the THz FBG signal related with the ambient change. To extract the THz FBG signal shift, a self-mixing technique was applied to the extracted individual THz FBG signal. The reflected signal

in frequency domain is squared and filtered using a low-pass filter to obtain the FBG reflection spectrum:

$$S = 2\eta^2 r^2 I_{ref}^2 \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} \cos[2\beta(i-j)\Delta z]$$

Figure 2.3 shows both simulation and experimental results from 1 mm and 0.1 mm THz FBGs. Both structures were fabricated with 20 reflection points using a fs laser at 0.11 W power. Some noise features are evident in the experiment signals, which are attributed to imperfections introduced during fabrication. The simulation results agree well with the experimental data.

Experimental Results and Discussions

In order to determine the effect of varying the number reflection points on signal quality, the full width at half maximum (FWHM) of signals from gratings with differing numbers of reflectors were measured. Three THz FBGs were fabricated using the same period (1 mm) and same fabrication power (0.11 W), and with 10, 20, and 40 reflection points, respectively. Data were sampled 100 times from each THz FBG. The average FWHM results for the 10, 20, and 40 reflection point THz FBGs were 7.03 GHz, 3.85 GHz, and 1.27 GHz, respectively. These results indicate that, when period and fabrication power are held constant, increasing the number of reflection points of a THz FBG results in enhanced signal quality factor (Q-factor). However, the trade-off is the mitigated spatial resolution due to the increased grating length.

To investigate the potential utility of a THz FBG as a temperature sensor, a THz FBG was fabricated using a fs laser power of 0.11 W, a period length of 1 mm, and 20 reflection points. The THz FBG was placed in a temperature-controlled water bath and

Figure. 2.4. Temperature response: (a) 1 mm THz FBG reflection spectra at 65 °C and 55 °C; (b) cross-correlation pattern to extract the frequency shift from (a); (c) frequency shift as a function of temperature

the sensor's temperature response measured. Figure 2.4 (a) shows the THz FBG frequency signal at both 55 °C and 65 °C. As the temperature increases, the period of FBG increases, causing a corresponding shift in resonant frequency. The frequency shift can be extracted by calculating the cross-correlation pattern. Figure 2.4(b) shows the normalized cross-correlation pattern from Figure 2.4(a) with a frequency shift of 12.84 GHz. Figure 2.4(c) plots the temperature response from 50 °C to 65 °C. Using this configuration, the temperature sensitivity for the THz FBG was observed to be approximately -1.32 GHz/°C. It is worth noting that the sensitivity of THz FBG is much larger than conventional microwave grating due to the fact that the interrogation window in the proposed setup is in optical range, and the grating resonant peak under test is at a much higher order in comparison with 1st order in a microwave grating. For 1 mm grating, the resonant peaks range from 1923th to 1967th order, given that the laser tuning bandwidth is from 1525 to 1555 nm.

In order to investigate the distributed sensing capability of the system, a 40-reflection point THz FBG was fabricated with a period of 1 mm, shown in Figure 5(a).

Figure 2.5. Distributed sensing test with THz FBG array: (a); a time-domain 40 reflection point THz FBG signal; (b) frequency-shift distribution measured using THz FBG array.

The system was calibrated using the reflectivity of an APC connector, which was previously measured to be -60 dB using precision instrument. The reflectivity of each point is around -70 dB. The reflectivity of each reflection point varies due to imperfections in the fabrication process. The reflection spectra of THz FBG were first measured with no temperature change as reference. An ice cube was then placed ~1 cm away from the THz FBG close to center in order to introduce a temperature distribution along the fiber sensor. The spectra were again taken and a high order 0.1 ns time-domain moving filter, corresponding to 1 cm in spatial domain, was used to gate the FBG signal with a step of 1 mm. 90% of the filter window overlapped with its neighboring filter window. The frequency shift as a function of filter start position was plotted in Figure 2.5 (b). A Gaussian-like temperature distribution was observed in which the center THz FBG experienced a frequency shift corresponding to a temperature approximately 1 °C lower than that of either edge of the THz FBG sensor. A real-time experimental demo was videotaped and attached to this letter. This experiment demonstrates that THz FBGs hold the potential for continuous distributed sensing with high spatial resolution. In

Figure 2.6. Temperature response of 1mm THz FBG using different laser sweeping ranges: (a) - (c) temperature response with 3 interrogation bandwidth, (d) temperature test with different interrogation bandwidth

addition, the ultraweak reflection nature of so fabricated THz FBGs promises a huge multiplexing capacity [27].

A key feature of THz FBGs is that they require a much narrower detection bandwidth than FBGs in the optical frequency range while maintaining good spatial resolution. To demonstrate this feature, a THz FBG with 20 reflection points was tested using differing sweeping bandwidths from a tunable laser. Figure 2.6 (a-c) shows the spectra of the sensor under test using these differing laser sweep bandwidths. Figure 2.6 (d) shows the temperature response for each different bandwidth, which are observed to agree well with each other. These results demonstrate that, when compared with a conventional optical FBG, use of a THz FBG can effectively reduce detection bandwidth.

To evaluate system-level accuracy, a stability test was conducted by fixing the temperature of a 1 mm, 20 reflection point THz FBG. 100 spectra were recorded using

this configuration. The frequency shift of each spectrum relative to its initial status was calculated. The standard deviation of the frequency shift was less than 2.27 MHz. Given the experimentally measured sensitivity of $-1.32 \text{ GHz}/^{\circ}\text{C}$, its temperature detection limit is calculated to be less than 0.0017°C . This demonstrates that THz FBG holds significant potential for high-accuracy detection. The temperature sensing dynamic range is limited by the free spectral range (FSR) of THz FBGs. Frequency shift beyond FSR will result in spectral ambiguity problem. For example, 1 mm THz FBG has a FSR of $\sim 100 \text{ GHz}$, corresponding to a dynamic range of $\sim 76^{\circ}\text{C}$. The dynamic range is inversely proportional to the pitch length of THz FBG. In addition, large dynamic range requires wide interrogation bandwidth.

Conclusions

To conclude, this letter reports the development of a FBG operating in the terahertz range with the demonstrated potential to combine the high spatial resolution of FBGs with the narrow detection bandwidth of CCBGs. The effect of varying the number of reflectors on signal quality was quantified. The potential of a THz FBG as a temperature sensor was experimentally validated, with a sensitivity of $-1.32 \text{ GHz}/^{\circ}\text{C}$ and a detection resolution of less than 0.0017°C . The utility of THz FBGs for distributed sensing with high spatial resolution was experimentally demonstrated. Similarly, differing interrogation bandwidths (0.5 THz, 0.1 THz, and 40 GHz) were shown, in Figure 2.6, to have identical temperature sensitivities, illustrating that THz FBGs can be successfully interrogated using narrower bandwidths than current optical FBGs.

3. Ultra-weak waveguide modification with femtosecond laser pulses

by

Zhen Chen, Gerald Hefferman, Lei Yuan, Yang Song and Tao Wei

published in

Photonics Technology Letters, IEEE, vol. 27, no. 16, pp. 1705 - 1708, Jun. 2015.

Abstract

This letter reports a new fabrication technique to inscribe in-line, ultra-weak waveguide structures. To the best of the authors' knowledge, this is the first time that an in-line grating structure has been fabricated within the core of an optical fiber with an intact buffer coating, allowing the fiber to retain optimal mechanical properties, an important consideration for strain and temperature sensing applications. Low energy pulses from a femtosecond laser were adjusted to avoid buffer absorption while inscribing a terahertz fiber Bragg grating (THz FBG) within the optical fiber core. Strain and temperature tests were conducted using both a THz FBG sensor fabricated using the reported method and a second THz FBG fabricated using a previously reported method requiring buffer removal. Highly similar results from both THz FBGs were observed, indicating that the new intact buffer fabrication technique holds substantial potential as a method of fabricating optical fiber grating structures for distributed sensing applications.

Introduction

Femtosecond laser has been attracting more interests in micromachining [28, 29]. Due to the non-linear absorption, the laser induced breakdown could precisely deliver the high-intensity energy to the focal point causing minimum damage to the surrounding material [30]. The ultra-short pulse could effectively introduce the refraction index change to transparent material. With the modification by femtosecond laser, regular single mode fiber can be used to fabricate the high sensitive optical devices, including Fabry-Perot cavity, fiber Bragg grating, long period grating, substrate/probe for surface enhanced Raman spectroscopy (SERS) detection, etc. [1, 10, 13, 26, 31-38].

Recently, terahertz fiber Bragg grating (THz FBG) was successfully fabricated by the femtosecond laser [16]. The pitch length was setup in sub-centimeter scale to achieve the THz domain detection. Ultra-weak (<-80 dB) reflectors were periodically seeded along the single mode fiber and no crosstalk was found. The THz FBG holds the great potential for high resolution distributed sensing. Before the fabrication of the THz FBG, it is necessary to remove the buffer from femtosecond laser processing region due to the different material absorption between the buffer coating and silica glass. However, practically the bare fiber is easy to break with poor mechanical property. It is hard to handle the bare fiber without the coating material during the fabrication process. The THz FBG sample was also fragile during the delivery and testing. This is especially true for long distributed THz FBG arrays. Although it is possible to recoat the bare fiber sensor with UV curable material after the fabrication, the recoating length was limited. Here stresses the engineering challenge: during the femtosecond laser fabrication, can we process the sample without stripping the buffer.

This letter reports a new femtosecond (fs) laser fabrication method to modify the ultra-weak waveguide structure on the THz FBG sensor. The buffer was able to remain on the sensor during the fs laser fabrication process, which significantly enhance the mechanical prosperity of the sensor. Experiments were conducted between the THz FBG with previous fs laser fabrication method and the one we proposed with intact polymer buffer coating. Highly similar results were observed.

Operation Mechanism

Both grating structures were interrogated using optical frequency domain reflectometry (OFDR) [17, 18] and fabricated using a Ti: Sapphire fs laser (Coherent,

Inc.) micromachining system. Single mode optical fiber (Corning, SMF-28) with core and cladding diameters of 8.2 and 125 μm , respectively, and a dual acrylate buffer was used in the fabrication of both gratings.

Figure 3.1 Schematic of femtosecond laser fabrication

In the case of the stripped-buffer grating, the laser power used during fabrication was 0.11 W, resulting in the creation of a weak core mode reflection. This laser power was strong enough to be absorbed by the buffer material of the optical fiber to melt and deform the polymer layer, defocus the fs laser beam and fail the grating fabrication. This justifies the necessity to remove the buffer prior to fabrication of the grating structure. Reflection signals recorded using this method were measured to be 22 dB above the Rayleigh level, which was considered the noise floor in this study, offering good signal quality for detection. Figure 3.2 (a) shows a THz FBG (41 reflectors, or 40 periods, pitch length 1 mm) fabricated using this earlier method requiring buffer removal.

In order to fabricate a similar grating structure in which the buffer layer of the fiber under process was preserved, fs laser power was adjusted to 0.085 W; at this reduced level, the laser energy was not absorbed by the dual acrylate coating at a level sufficient to melt the fiber buffer. It is worth noting that the melting power of buffer materials under this setup is 0.05 W when laser beam is focused on polymer coating. The power 0.085 W used in grating fabrication here is focused on the fiber core, explaining that it is 70% higher than the threshold power to melt polymer. While core reflectors were still inscribed along the length of the fiber under process, these perturbations within the optical fiber core were reduced to the point of being invisible using conventional light microscopy. Signals recorded from these reflectors were measured to be 10 dB above the noise floor, again sufficient for good signal quality. Figure 3.2 (b) shows a THz FBG (41 reflectors, pitch length 1 mm) fabricated using this proposed method. No insertion loss was found.

Figure 3.2 Distance domain signals for THz FBG fabricated by femtosecond laser: (a) with buffer coating stripped; (b) proposed method with buffer

Experimental Results and Discussions

To investigate the utility of the sensor constructed using an intact buffer, both the sensors in Figure 3.2 were interrogated in series and subjected to identical strain and temperature testing for direct comparison.

In order to conduct a strain test, one end of the optical fiber under test housing both grating structures was secured to an optical bench with the other end free to hang. Weights were sequentially added to the free end of the fiber in 3 g intervals; in total, 30 g were added to the free end of the fiber under test. The results of this strain test for both grating structures are shown in Figure 3.3 (a). A linear relationship was found between the accumulated screw weight and frequency shift, with an R^2 values for both grating structures greater than 0.9998 and slopes of 1.8695 GHz/g and 1.7993 GHz/g for the uncoated and buffer-coated gratings, respectively. The slight discrepancy between these two slopes is surmised to be attributable to the difference in effective Young's modulus between the two sensors, the result of mechanical differences between with or without the impact buffer coating.

Figure 3.3 Strain and temperature test with two different THz FBGs: (a) strain test results; (b) temperature test results

Similarly, to the strain testing set-up, temperature sensing using the two gratings was conducted by simultaneously interrogating the two sensors in series with both

sensors submerged within a water bath. The water was first heated to 65°C, and then cooled to 55°C. The test results are for both grating structures shown in Figure 3.3 (b). A linear relationship was found between the temperature drop and the sensor frequency shift, with R² values for both gratings greater than 0.9994 and trend line slopes of -1.2791 GHz/°C and -1.3041 GHz/°C for the uncoated and buffer-coated gratings, respectively. As the heat capacity of water is larger than the buffer coating material, the sensor with the intact buffer coating cooled slightly faster than the grating without the buffer coating, which is surmised to account for the slight difference between the two-temperature testing result trend line slopes.

The results of both strain and temperature testing demonstrate that the fiber grating structure with an intact buffer coating has analogous sensing capabilities to the uncoated grating structure fabricated using conventional methods.

Conclusions

To conclude, this letter reports a new femtosecond laser fabrication method to modify the ultra-weak waveguide structures. To our best of knowledge, this is the first time to process the fiber sensing device without stripping the buffer. The fs laser output power was carefully adjusted to avoid the buffer coating melt and deformation, which enables grating fabrication with intact buffer, and largely enhances the sensor mechanical property. Strain and temperature test were conducted on both the uncoated buffer THz FBG sensor and the coated one. Highly identical results were observed, indicating that the proposed method holds great potential for distributed sensing measurement.

4. Phase-shifted terahertz fiber Bragg grating for strain sensing with large dynamic range

by

Gerald Hefferman, Zhen Chen and Tao Wei

published in

Photonics Technology Letters, IEEE, vol. 27, no. 15, pp. 1649 - 1652, Jun. 2015.

Abstract

Recent advances in optical fiber sensing techniques have demonstrated the utility of terahertz (THz) gratings as a modality for strain and temperature sensing. However, these techniques remain reliant on the use of higher-order resonant peaks, enhancing their sensitivity at the cost of limited dynamic range. The use of a lower-order resonant peak for sensing can lead to a larger dynamic range at the cost of accuracy. This letter reports a π -phase-shifted THz fiber Bragg grating, fabricated using a femtosecond laser, capable of detecting changes in strain over a substantially larger dynamic range than previously reported methods with improved accuracy. A second THz grating without a π -phase-shifted structure, but otherwise identically constructed, was interrogated in series on the same optical fiber. The two devices were simultaneously experimentally investigated using a strain test (~ 1.0 m ϵ in total), and the results presented in this letter. Additionally, theoretical models of the devices were created, which closely matched experimentally observed device physics.

Introduction

Optical fiber sensors have a unique set of characteristics that make them particularly useful as strain and temperature sensors [23, 26, 34-36, 39-41]. Their chemical stability and immunity to electromagnetic interference make them ideally suited to sensing in harsh environments, while the ease with which multiple sensors can be fabricated in series and simultaneously interrogated allows for multiplexed sensing across considerable distances ($\sim$ km), making optical fiber sensors a viable solution in structural health monitoring, energy, and aerospace applications [1, 13, 42, 43].

Fiber Bragg gratings in particular have demonstrated their utility in these areas, and

are a fundamental element of many optical fiber sensing techniques. Recently, fiber Bragg gratings fabricated with grating structures corresponding to the terahertz range (THz FBGs) have demonstrated additional characteristics that make them particularly well-suited to applications requiring large-scale, multiplexed sensing techniques [24, 44]. Chief among these advantages are their narrow interrogation bandwidth (hundreds of gigahertz) and their high spatial resolution (<1 mm).

Figure 4.1 Experimental set-up and time-domain plots of the optical fiber under test. (a) Diagram of the strain testing set-up; (b) time domain plot of optical fiber with both the π -phase-shifted and unmodified THz FBGs in series; (c) detail of the time-domain trace at the area of the π -phase-shifted THz FBG; (d) detail of the time-domain trace at the area of the unmodified THz FBG.

Despite these advantages, however, current THz FBG sensing techniques remain limited by their relatively narrow dynamic range. This limitation is chiefly due to the use of higher-order resonant peaks (1923rd to 1967th order with a pitch length of 1 mm) for parameter measurement and signal processing, which reduces dynamic range [44]. This trade-off is particularly limiting in the case of structural health monitoring, an area in which the need for structural data gathered during episodes of high strain and

temperature is particularly acute. On the other hand, the use of lower-order resonance peaks at lower frequencies can resolve this ambiguity problem at the cost of decreased sensitivity.

It is known that the quality factor of the resonance peak can be significantly improved by introducing a defect into periodic structures, such as photonic crystals or FBGs [20, 45, 46]. This letter reports a grating structure interrogated in the terahertz range that surmounts this limitation. By interrogating the structure using lower-order (9th order) resonance peaks and introducing a π -phase-shift into a THz FBG structure, the dynamic range of the resulting sensor was substantially increased and the corresponding loss of accuracy minimized, respectively. Experimental investigation of the π -phase-shifted THz FBG was conducted and compared against a THz FBG that was not phase-shifted, but was otherwise identically fabricated and interrogated in series along the same optical fiber. The results of this investigation, as well as a theoretical simulation modeling device physics, are presented in this letter.

Operation Mechanism

Optical frequency domain reflectometry (OFDR) was used as the interrogating system in this study [47]. The theoretical framework used to model the π -phase-shifted THz FBG is as follows: M π -phase-shifted THz FBGs are embedded along the detection arm of the system, with each π -phase-shifted FBG containing N reflectors (N is even) and a pitch length Δz . The total AC coupled voltage received by the DAQ can then be expressed as:

$$v_{total} = 2\eta I_{ref} \sum_{m=0}^{M-1} \left\{ \sum_{n=0}^{N/2-1} \cos[\beta(z_{ref} - z_m - 2n \Delta z)] \right. \\ \left. + \sum_{n=N/2}^{N-1} \cos[\beta(z_{ref} - z_m - 2n \Delta z)] \right\}$$

where η is the light-to-voltage conversion coefficient of the photodiode, r is the reflection coefficient of the FBG reflectors, I_{ref} is the light intensity of the reference arm, β is the propagation constant, z_{ref} is the length from the reference arm to the photodiode (PD), and z_m is the length from the start of the m^{th} grating to the PD. The intensity of the reflected light can be obtained using an inverse Fourier transform. In this study, Rayleigh scattering is defined as the noise floor, resulting in a signal-to noise ratio (SNR) of approximately 25 dB. Signals from a target FBG along the fiber under test can be extracted via a band-pass filter. The sensing mechanism is based on tracking the frequency shift of the THz FBG signal, which is related to ambient change—in this case, strain along the fiber under test.

Figure 4.2 Simulation results and experimentally collected spectrum of the π -phase-shifted THz

Data from the π -phase-shifted THz FBG is extracted from the total M FBGs using a Butterworth band-pass filter; data from the unmodified THz FBG is similarly

extracted. By applying a Fourier transform and discarding the phase information gathered by OFDR, the time domain signals of both gratings can be found, as shown in Fig. 1 (a-c). As the number of detection points is cut by half using this method, the signal bandwidth is 1.85 THz. Applying a second Fourier transform on the resulting time domain scanning signal yields a frequency domain periodic signal in the THz range.

Fig. 2 shows theoretically-modeled and experimentally observed frequency domain signals generated using this method. Simulated data was generated using a pitch-length of 0.9825 mm, a reflectivity of 10^{-6} , and a bandwidth of 3.8 THz. Peak shift in this signal is related to strain change along the length of the fiber under test. The 9th order resonance peak of the frequency domain signal was used in this test.

Experimental Results and Discussions

In order to experimentally investigate the sensing utility of the π -phase-shifted fiber Bragg grating, a strain test was conducted. A Ti:Sapphire femtosecond laser (Coherent, Inc.) was used to fabricate both gratings within single-mode optical fiber (Corning, SMF-28) at a laser power of 0.11 W [37, 38]. Each grating contains 18 reflection cavities with a pitch-length of 1 mm. A π -phase-shift (1.5 times the pitch length) was added halfway along the length of the phase-shifted THz FBG.

Both the π -phase-shifted and unmodified THz FBGs were tested in series and interrogated simultaneously. The optical fiber with both sensors was secured to an optical bench on one end, with the other end free to hang. Weights were sequentially added to the free end of the optical fiber, and the resulting output from each sensor was recorded using the method described above. In all, 20 weights, with a total mass of 124

g, were added to the free end of the fiber at 6.2 g intervals. In order to quantify the strain change along the optical fiber generated by the addition of each set of weights, the unmodified THz FBG was interrogated using higher order modes, as described in previous work [44]. Due to the fact that the sequential addition of each weight to the fiber under test resulted in an incremental phase shift of less than 2π radians, this method provided a direct measure of strain along the fiber. Importantly, however, the total change after the addition of all the weights resulted in a combined shift greater than 2π radians using higher-order modes, which is beyond the detection limit of the earlier approach, but within the limit of the method described in this letter. Using this technique, total strain change of 1.0 m ϵ in intervals of approximately 71.5 $\mu\epsilon$ was measured over the course of the experimental trial.

Figure 4.3 Experimental results of strain testing along the optical fiber under test. (a) Spectra of π -phase-shifted THz FBG; (b) spectra of unmodified THz FBG; (c) relative peak shift of the π -phase-shifted THz FBG as a function of strain and best-fit trend line; (d) relative peak shift of the unmodified THz FBG as a function of strain and best-fit trend line. Points and curves of the same color were collected and calculated simultaneously as weights were sequentially added to the fiber under test.

As both sensors were placed along the same optical fiber and tested simultaneously, crosstalk between the two sensors was considered. By using ultraweak reflectors in the

fabrication of both grating structures (-60 to -70 dB), crosstalk between the two THz FBGs was effectively minimized [24]

The results of this experiment are shown in Fig. 3. The comparison between the spectra of π -phase-shifted THz FBG and unmodified THz FBG clearly showed that the quality factor of the resonance peak/dip improves by introducing a π -phase-shift into the normal THz FBG. As a result, the π -phase-shifted THz FBG demonstrated much improved linearity between strain change and frequency shift, with a R^2 value of

0.9962 and a trend-line slope of -0.0011 GHz/ $\mu\epsilon$. In contrast, data collected from the unmodified THz FBG demonstrated less linearity, with an R^2 value of 0.6699. These results demonstrate that the π -phase-shifted THz FBG performed substantially better than the unmodified THz FBG in the detection of strain changes along the length of the optical fiber under test. In addition, as observed in the experiments, the intensity of reflection spectrum decreases as the loaded strain increases. This is attributed to the fact that the refractive index contrast, or reflectivity, of the fs modified reflectors decreases under strain. Importantly, the experimental results also showed that the signal of the proposed THz FBG was sufficiently strong for strain sensing within the testing range up to 1 m ϵ .

Conclusions

To conclude, this letter demonstrates that the application of a π -phase-shift to THz FBGs provides the enhanced accuracy necessary to use lower-order resonance peaks for sensor interrogation, allowing for expanded dynamic range relative to the previously reported method using higher-order resonance peaks. This sensing strategy was theoretically-modeled and experimentally investigated using both a π -phase-shifted

THz FBG and an unmodified THz FBG in series along the same optical fiber under test. The resulting linearity of the peak shift of the π -phase-shifted THz FBG ($R^2 = 0.9962$) demonstrates that this technique has the potential to lead to the application of THz FBGs to domains in which large dynamic range is a critical engineering requirement. Structural health monitoring provides an example of one such area; by allowing for enhanced real-time monitoring of critical infrastructure, THz FBGs with enhanced dynamic range have considerable potential societal benefit.

5. Terahertz-range interrogated grating-based two-axis optical fiber inclinometer

by

Zhen Chen, Gerald Hefferman, Lei Yuan, Yang Song and Tao Wei

published in

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Abstract

This manuscript reports a two-axis fiber inclinometer fabricated using an ultraweak terahertz-range fiber Bragg grating (THz FBG). Three sensing grating structures were inscribed along a single-mode optical fiber using a femtosecond laser, bound together into a sensing array using thermoformed plastic, and fixed to a two-axis rotation stage. Inclination tests were performed in which the fiber was deflected from 0° to 1.7° . These tests were repeated at eight azimuthal angles in increments of 45° (from 0° to 315°). The standard deviation of the largest inclination angle error was 0.048° and the stability of the inclination angle was 0.030° .

Introduction

Optical fibers have seen increasing use as sensing elements for strain, stress, temperature and refractive index measurements in a wide variety of engineering applications. A more recent application of fiber sensors is to determine angle and position information used for three-dimensional shape sensing. Due to its compact size and ability to conform to relatively complex shapes, optical fiber can be easily fixed along an object of interest to mirror its orientation. Multiple strain sensors can then be integrated together to form a single sensing probe aligned to the changing contour along the object. By using a multi-core fiber or a multi-fiber bundle packaging method, three or more strain sensors can be packaged in parallel together as one sensing element to measure strain information in three dimensions, data that can ultimately be used to find the angle and position information necessary for three-dimensional shape sensing.

Different fiber distributed strain sensors have been proposed and commercialized to reach this engineering goal. The two main research areas undergirding this

technology are fiber Bragg gratings (FBG) and coherent optical frequency domain reflectometry (C-OFDR). Both methods use differing fundamental physics to reach the same goal; distributed strain sensing along an optical fiber.

A fiber Bragg grating (FBG) is a wavelength-based fiber sensor [14, 48]. Periodic reflectors are inscribed along a single mode fiber by UV laser to form a wavelength-specific dielectric mirror that reflects a certain wavelength and transmits the rest. Multiple FBGs can be integrated along one sensing probe using wavelength multiplexing to achieve distributed strain measurements. Miller et al. have proposed several FBG-based structures used to resolve the spatial angle information using multiple FBGs, which include multi-core fibers [49, 50] and three-fiber bundles [51] as two-axis fiber inclinometers. More recently, researchers have demonstrated using a femtosecond laser to directly inscribe FBG waveguide structures into a single coreless fiber [52] and standard single mode fiber [53] for three-dimensional shape sensing applications.

Coherent optical frequency domain reflectometry (C-OFDR) [2, 5, 54-59] is an alternative, state-of-the-art distributed sensing technology. By sweeping the optical frequency with a tunable laser, the Rayleigh backscatter profile along an optical fiber can be measured, which correlates to strain along the fiber under test. This interferometric measurement is capable of maintaining a terahertz-level detection bandwidth with high spatial resolution. Using three or more probes, C-OFDR has successfully demonstrated its ability to deliver three-dimensional shape sensing using both the multicore fiber [60-62] and multiple fiber packing methods [63].

Recently, the use of terahertz fiber Bragg grating (THz FBG), an extension of C-OFDR interrogation, has been demonstrated [44, 64]. A high-power femtosecond laser is employed to inscribe ultra-weak periodic reflectors (< -70 dB) within the core of a standard single mode optical fiber, providing distributed interferometric strain measurements along the fiber under test and allowing the system to achieve enhanced sensitivity compared with traditional Rayleigh scattering-based (< -80 dB) C-OFDR techniques. By combining three or more of these THz FBG sensors into a single fiber sensor bundle, the system is able to determine the spatial angle information necessary to act as a two-axis optical fiber inclinometer, an important step towards three-dimensional shape sensing.

This manuscript reports a terahertz fiber grating-based two-axis optical fiber inclinometer fabricated using ultra-weak reflection arrays (-70 dB). Three identical THz FBGs were aligned and packaged as a single fiber bundle. The differing strain distributions across the three THz FBGs within the sensing probe were measured and used to determine the spatial angle information along the fiber bundle. The inclinometer was tested at eight azimuthal angles (from 0° to 315°). The standard deviation of the greatest inclination angle error was 0.048° and the inclination angle stability was 0.030° . No cross-talk was found between the ultra-weak reflection arrays.

Operation Mechanism

In order to experimentally investigate the terahertz grating-based inclinometer concept, a 30 mm-long inclinometer was constructed. Three identical THz FBGs were fabricated with intact buffer coatings using single mode fiber (SMF-28, Corning) and a Ti: Sapphire fs laser (Coherent, Inc.) micromachining system [11, 24, 34, 38, 65]. Each

sensing array contained 41 ultra-weak reflectors ($\sim -75\text{dB}$) with a pitch length of 1 mm. To bind the modified fibers into a three-fiber bundle, the three SMF fibers with THz FBG arrays were secured equidistant to one another, as shown in Figure 5.2 (a). The three modified fibers were aligned using reference marks ~ 5 cm beyond the length of the sensing arrays. Two 40 mm heat melt tubes (EVA) and a 90 mm heat shrink tube were placed outside the aligned sensing arrays, as illustrated in Figure 5.1 (a). Hot air ($\sim 300^\circ\text{F}$) was blown from ~ 1 cm away and swept across the length of the bundle at a speed of ~ 1 cm/s. After subsequent cooling, the three THz FBG sensing arrays were firmly fixed in place, shown in Figure 5.1 (b).

Figure 5.1 Three-core fiber inclinometer bundle packaging and assembling: (a) before heated, (b) after heated, (c) schematic of the assembling the fiber inclinometer

To assemble the inclinometer, one end of the packaged bundle was positioned using a screwed ferrule into the center of a 360° rotational mount (Newport Inc.) along the Z axis to give azimuthal rotation control, as illustrated in Figure 5.1 (b). The other end

was affixed to a micrometer-level stage that could be moved vertically in the Y direction, enabling inclination angle control.

Figure 5.2 Schematic of cascaded THz FBG sensors: (a) the time domain interrogation signal of three identical THz FBG sensing arrays, (b) the details of sensing array 1, (c) the packaged inclinometer bundle

To conduct the inclination measurement experiment, three THz FBG sensing arrays were cascaded in-line, as shown in Figure 5.2, and interrogated via coherent optical frequency domain reflectometry (C-OFDR). For each sensing array, a 10 mm time-domain moving filter was applied to measure the distributed strain along sensor; in total, 7 strain measurements at 5 mm steps were extracted. The three strain sensing points at the same position along the inclinometer bundle then form a single sensing element; in total, 7 sensing elements along the 30 mm sensor were used. Each sensing element contains three-dimensional strain information, which can be used to calculate the spatial position in the three-dimensional Cartesian coordinate system with Frenet-Serret

formulae (16). The azimuthal angle φ was defined as the sensor rotation along the Z axis. As the sensor was deflected towards the Y+ direction, the inclination angle θ at a certain azimuthal angle φ , shown in Figure 5.3 (b), was defined as the acute angle between the Z axis and line passing through the 6th and 7th sensing elements.

Figure 5.3 Schematic of the measured inclination angle: (a) 3D representation, (b) 2D representation (project to YZ plane)

In order to account for packaging inconsistencies such as sensing array misalignment or heat shrink tube nonuniformity, calibration must be performed. First the cross-plane of each sensing element, the relative positions of the three strain sensing points were calibrated. As illustrated in Figure 5.4 (d), the bundle was bent towards three different azimuthal angles φ_1 , φ_2 , and φ_3 , where sensing arrays #1, #2, and #3 were each positioned on top, respectively. The differing strain distributions for the seven sensing points were then measured along each sensing array. For each sensing element, a two-dimensional cross-plane was extracted to calculate the relative position of the

three strain sensing points. At each sensing element, the balanced boundary condition can be expressed as:

$$\frac{\varepsilon_{i1}}{d_{i1}} = \frac{\varepsilon_{i2}}{d_{i2}} = \frac{\varepsilon_{i3}}{d_{i3}}$$

Figure 5.4 Calibrate the relative position: (a) - (c): the cross-plane illustration of bending with sensing array #1, #2 and #3 on top respectively, (d) schematic of inclination bending

where ε_{ij} is the strain measurement with the i th sensing array on top (at azimuthal angle φ_i) for the j th sensing array and d_{ij} is the related length of lever arm. It is assumed that the bending is occurring across the center of the sensor at origin (0, 0) in the two-dimensional plane. The line perpendicular to the bending direction and passing the origin (0, 0), can be expressed as:

$$A_i x - y = 0$$

where A_i is the slope of the line with i th sensing array on top. At a certain sensing element cross-plane, the relative position of i th sensing array on top at the j th sensing array can be expressed as (x_{ij}, y_{ij}) . The related length of lever arm d_{ij} shown in Figure 5.4 (a) - (c), can be expressed as:

$$d_{ij} = \frac{A_i x_{ij} - y_{ij}}{\sqrt{A_i^2 + 1}}$$

The initial condition is defined where the relative distance between the sensing points along sensing array #1 to the X-axis is normalized to 1. The relative positions of the three sensing points for each sensing element cross-plane were then solved, shown in Figure 5.5. These coefficients were converted to polar form and applied to solve the Frenet-Serret equations.

Figure 5.5 Calibrate the relative position: (a) with sensing array #1 on top, the strain measurement result along the three sensing arrays, (b) the solved relative position on the 1st sensing element cross-plane

Second, the absolute radius can be calibrated based on the assumption that all seven strain sensing points along the sensing array #1 share the same distance to the center of the inclinometer bundle. Based on the first calibration results, another radius coefficient is set to match the calculated position and the absolute deflection by the Y-directional stage at each azimuthal angle.

Experimental Results and Discussions

To investigate the utility of the fiber inclinometer, inclination angles from 0° to 1.7° with a step of 0.085° were investigated for all eight azimuthal angles (0° , 45° , 90° , 135° , 180° , 225° , 270° and 315°). Some of the representative measurement data are plotted in Figure 5.6. The calibration coefficients were implemented before inclination testing. The inclination test results at azimuthal angle 0° and 270° are shown in Figure

Figure 5.6 Two-axis inclination measurement results: (a) measured inclination angles $\theta = 0^\circ$, 0.767° and 1.70° , respectively, at eight differing azimuthal angles (φ) (45° apart from 0° to 315°) (b) measured inclination angle against calculated angle at $\varphi = 0^\circ$, (c) measured inclination angle against calculated angle at $\varphi = 270^\circ$

5.6 (b), (c). Similar results were found with other azimuthal angles. The largest error standard deviation was 0.048° .

The stability test of the proposed inclinometer was conducted with a fixed 0° azimuthal angle and 0° inclination angle. In total 250 sets of tests were repeated to measure this initial inclination angle. The standard deviation of the measured angle was 0.030° , indicating a good repeatability of this device.

The maximum inclination measurement range was 2.5° with steps of 0.085° and the error standard deviation was 0.036° . In these tests, the inclination measurement range was limited by the maximum frequency shift within 1 period of the implemented THz FBG, which is 100 GHz for 1 mm pitch length.

Conclusions

To conclude, this manuscript reports a new two-axis optical fiber inclinometer based on terahertz fiber Bragg grating (THz FBG) structures. Inclination angles from 0° to 1.7° were tested at eight azimuthal angles (from 0° to 315°), covering one full rotation. The standard deviation of the largest inclination angle error was 0.048° and the observed inclination angle stability was 0.030° . In addition, the 3-dimensional spatial positions for all sensing elements were solved, indicating this sensor holds substantial potential for three-dimensional distributed sensing.

6. A low bandwidth DFB laser-based interrogator for terahertz-range fiber Bragg
grating sensors

by

Zhen Chen, Gerald Hefferman and Tao Wei

published in

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Abstract

This letter reports an all-electronic, low bandwidth swept frequency laser used to interrogate terahertz-range fiber Bragg gratings (THz FBGs) for distributed strain sensing applications. A distributed feedback (DFB) laser with current injection modulation was employed as the swept frequency laser source. Using the resulting narrow bandwidth (~ 110 GHz) laser frequency sweep, high accuracy distributed strain measurements were achieved. In order to experimentally investigate this concept, a strain test was conducted using terahertz-range fiber Bragg gratings. During the test, the laser sweeping time was limited to less than 2 ms. Highly linear results were found ($R^2 = 0.996$), with an observed sensitivity of -0.142 GHz/ $\mu\epsilon$ and the standard deviation of 1.167 $\mu\epsilon$. A multiplexing test was also conducted, and no cross-talk found between sensor elements. These results demonstrate that this interrogation system holds substantial potential as a method of rapid distributed optical fiber frequency-domain sensing.

Introduction

Terahertz fiber Bragg gratings (THz FBGs) have been investigated as sensor elements for a number of distributed strain and temperature sensing applications [44]. Femtosecond laser micromachining techniques have been used to fabricate these millimeter-range weak periodic structures within the cores of otherwise unmodified communications-grade optical fibers [26]. The reflectivity of individual reflector elements can be controlled by adjusting the power of the femtosecond laser during fabrication, allowing the system to balance both signal-to-noise ratio and multiplexing capability. High accuracy measurement can be achieved by interrogating the sub-

terahertz range resonance periods of these THz FBGs at higher orders using an optical frequency sweep. More recently, low interrogation bandwidth (100 GHz) measurements have been effectively demonstrated using 1 mm pitch length THz FBGs.

Until recently, the interrogation systems used to probe THz FBGs have all been based on coherent optical frequency domain reflectometry (C-OFDR) [5, 54, 66], where a key component of the system is a highly coherent swept laser source. Previously, an external cavity laser was employed as the frequency sweep source, which allowed for the interrogation of THz FBGs using a broad sweeping bandwidth (~ 3.7 THz). When compared with the 100 GHz resonance period of the 1 mm pitch length THz FBG, however, this broad sweeping bandwidth may be unnecessary. External cavity lasers require the use of moving mechanical components in order to achieve a frequency sweep, limiting the update rate and increasing the system complexity. This combination of a broader-than-necessary bandwidth and slow update rate has led to increasing interest in the use of alternative swept laser interrogator techniques.

Several other highly coherent frequency sweep sources have been experimentally explored for use with C-OFDR systems; these include temperature and piezo-electrically tuned Nd: YAG ring lasers [67, 68], chirped distributed feedback (DFB) lasers [69] and piezo-electrically tuned fiber grating lasers [70]. Among these sources, the chirp-DFB laser represents a particularly promising candidate. The highly coherent optical frequency output of these lasers can be directly controlled by modulating the injection current. As this frequency modulation technique requires no mechanical movement of the laser cavity, the sweep time can be shortened, potentially increasing the update rate of the interrogation system. Additionally, a sweeping bandwidth of 100

GHz can be achieved, a suitable range for the interrogation of THz FBG sensors with a pitch length of 1 mm or greater. This letter reports a low bandwidth chirp-DFB laser-based interrogator for THz FBGs. A DFB laser with injection current modulation was used as the frequency sweep source to interrogate two THz FBG sensor elements.

This letter reports a low bandwidth chirp-DFB laser-based interrogator for THz FBGs. A DFB laser with injection current modulation was used as the frequency sweep source to interrogate two THz FBG sensor elements. An interrogation bandwidth of 110 GHz within 1 ms was achieved using the system. In order to experimentally investigate the system, a strain test was performed; highly linear results ($R^2 = 0.996$) were observed, with a sensitivity of $-0.142 \text{ GHz}/\mu\epsilon$ and a standard deviation of $1.167 \mu\epsilon$. A multiplexing test was also conducted, and no cross-talk observed between the sensor elements. These results demonstrate that this system holds substantial potential as a method of dynamic distributed strain sensing.

Operation Mechanism

A schematic of the interrogation system, based on coherent optical frequency domain reflectometry (C-OFDR) [25, 64, 71], is shown in Figure 6.1. An arbitrary wave

Figure 6.1 Schematic of the chirp-DFB laser-based C-OFDR interrogation system (LDC: laser diode controller; AWG: arbitrary wave generator; DAQ: data acquisition; DFB: distributed feed-back laser; CPL: coupler; CIR: circulator; DUT: devices under test; BPD: balanced photodiode).

Figure 6.2 The measured MZI radio frequency, or the chirp-DFB laser sweeping speed as a function of time using different voltage modulation waveforms: (a) an initial ramp input; (b) after 6 feedback pre-distortion iterations.

generator (AWG) is used to modulate the DFB laser via a laser diode controller (LDC). The resulting output of the DFB laser source is sent into the optical system via a 90/10 coupler (CPL), with 90% of the power directed into the detection path and 10% of the power directed into the clock path. The clock path is constructed using a Mach-Zehnder interferometer (MZI), with a constant delay length of 54.02 ns . The data path is constructed using two 3-dB couplers and an optical circulator (CIR). The reflected signals from devices under test (DUT) can be measured via this interferometry structure. An anti-reflection termination is used to prevent strong reflections from the end of the DUT. Two balanced photo diodes and a data acquisition card (DAQ) are used to record the resulting interferometric signals. The DAQ has a sampling rate of 130 MSa/s and 15-bit resolution, and is triggered by synchronization output from the AWG.

Inspired by the work of Satyan et al. [72], an iteration pre-distortion method is applied in order to increase the linearity of the laser sweep. A chirp-DFB sweep model can be established in which the laser output optical frequency can be expressed as:

$$\omega(t) = \omega_0 + K_L(i) \cdot K_0 \cdot V(t),$$

where $\omega(t)$ is the output frequency of the DFB laser, ω_0 is the initial start sweep optical frequency, $K_L(i)$ is the LDC current dependent gain, K_0 is the LDC external modulation voltage to current coefficient, and $V(t)$ is the output modulation voltage waveform from the AWG. To simplify the equation, a sweep coefficient $B(i)$ can be defined as:

$$B(i) = K_L(i) \cdot K_0$$

An extra MZI interferometer with two 3-dB couplers and a delay of 28.4 ns was constructed for this iteration process. The laser sweep speed $v(t)$, related with laser frequency $\omega(t)$, can then be measured using this MZI with a delay length of τ_d :

$$v(t) = \frac{d\omega(t)}{dt} = B(i) \frac{dV(t)}{dt} = \frac{\omega_{BPD}(t)}{\tau_d},$$

where $\omega_{BPD}(t)$ is the radio frequency output of the BPD after the MZI.

The iteration process is as follows: For the n^{th} round of sweep ($n \geq 0$) using the n^{th} AWG modulation waveform $V_n(t)$, the n^{th} laser sweep speed $v_n(t)$ can be measured based on eq. (3). Using the n^{th} sweep coefficient $B_n(i)$, the next round $(n+1)^{\text{th}}$ sweep coefficient $B_{n+1}(i)$ can be generated:

$$B_{n+1}(i) = \frac{v_n(t)}{\bar{v}} B_n(i), (n \geq 0)$$

where $\bar{v}$ is the target sweep speed and initial sweep coefficient $B_0(i) = \bar{v}$. The $(n+1)^{\text{th}}$ AWG modulation voltage waveform $V_{n+1}(t)$ can then be determined based on eq.(3):

$$V_{n+1}(t) = \int \frac{\bar{v}}{B_{n+1}(i)} dt, (n \geq 0)$$

For the first sweeping round ($n = 0$), the initial AWG output waveform $V_0(t)$ is set as a ramp function from 0 to 1 Volt over 1 ms. The resulting laser optical sweep speed $v_0(t)$ is measured using a short-time FFT algorithm and plotted in Figure 6.2 (a). The target

Figure 6.3 Strain tests using the chirp-DFB laser source: (a) strain sensing test setup; (b) time domain reflection signals of the DUT with a 0.12 W THz FBG; (c) frequency domain interferograms with varying applied strain values; (d) resulting frequency shift at the varying applied strain values.

frequency sweep speed was set to 140 GHz/ms. After 6 rounds of feedback pre-distortion iterations, the resulting measured laser sweep speed is plotted in Figure 6.2 (b). The DFB laser sweep from 0.1 ms to 1 ms is used to interrogate the THz FBG sensors, where the sweep speed is between 130 and 150 GHz/ms. After re-sampling the data using the reference clock arm, 6k data points are generated, covering an interrogation bandwidth of 110 GHz. A 1 ms DC voltage output follows the 1 ms pre-calibrated waveform to allow the laser sweep speed to return to zero.

A Ti:sapphire femtosecond laser micromachining system (Coherent, Inc.) was employed to fabricate the THz FBG sensing units [24, 73]. The pitch length was set to 1 mm, resulting in a 100 GHz resonance period, which can be fully covered by the

Figure 6.4 Stability test results using 200 iterative measurements

interrogator. Multiple THz FBGs can be spliced in-line to perform distributed sensing measurements. A C-OFDR system is then used to gather frequency-domain data from the THz FBGs. By employing different band-pass filters, the reflected frequency domain data from each multiplexed THz FBG can be isolated. Using self-mixing and a low pass filter, the frequency domain interferograms S of a THz FBG can be extracted and expressed as:

$$S = 2\eta^2 r^2 I_{ref}^2 \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} \cos[2\beta(i-j)\Delta z]$$

where η is the light-to-voltage conversion coefficient of the photodiode, r is the reflection coefficient of the THz FBG reflectors, I_{ref} is the light intensity of the reference arm, β is the propagation constant, N is the number of reflectors within the THz FBG, and Δz is the pitch length. The weak reflectivity feature of THz FBG sensors results in very low insertion loss and ignorable cross-talk among THz FBG sensors in a large array so that substantially more sensing elements can be cascaded in-line along one fiber probe using time-domain multiplexing method. The reflected spectrums of demultiplexed THz FBG sensors can be overlapped. The central frequency of a particular THz FBG can be calculated using this equation. Strain applied to the fiber under test expands or contracts the THz FBG reflector elements, resulting in a phase shift of the THz FBG interferogram. These phase shifts are ultimately used as a method of distributed strain quantification [74].

Experimental Results and Discussions

In order to experimentally investigate the chirp-DFB laser-based interrogator system, a strain test was conducted. One THz FBG with a pitch length of 1 mm and 20

Figure 6.5 Multiplexing test using two THz FBG sensors: (a) multiplexing test setup; (b) time domain reflection signals of the DUT with both the 0.12 W THz FBG and the 0.14 W THz FBG; (c) frequency shift interferograms of the 0.12 W sensor with different strain values applied; (d) frequency interferograms of the 0.14 W sensor with no additional strain applied during the same period.

reflector points was fabricated using 0.12 W femtosecond laser power and connected to the interrogation system. One end of the sensor under test was secured to an optical bench while the other end was left free to hang, shown in Figure 6.3 (a). Weights were sequentially added to the free end of the fiber at 1.4 g intervals; in total, 21 g of weights (247.2 $\mu\epsilon$) were added to the free end of the sensor under test [75]. The DFB laser was modulated with the pre-calibrated AWG waveform shown in Figure 6.2 (b), covering a total bandwidth of 110.0 GHz. The time domain reflected signal, calculated using a Fourier transform algorithm, is plotted in Figure 6.3 (b). The relative intensity was calibrated using an optical fiber APC connector as a -60 dB reference. The resulting frequency domain shifted interferograms are plotted in Figure 6.3 (c), and strain test results are plotted in Figure 6.3 (d). A linear relationship was found between the accumulated strain and frequency shift, with an R^2 value of 0.996 and strain sensitivity of -0.142 GHz/ $\mu\epsilon$, which is similar to the sensors fabricated using unmodified silica-based optical fibers [76]. A stability test was then conducted in which the sensor under test was fixed to an optical bench with no strain changes applied. 200 groups of

measurements were gathered; the frequency domain interferogram shifts were determined, shown in Figure 4, and resulted in a standard deviation of $1.167 \mu\epsilon$.

To demonstrate multiplexing capability, another 1 mm pitch length, 20-point THz FBG was fabricated using 0.14 W femtosecond laser power and cascaded in-line with the first THz FBG, as shown in the schematic setup in Figure 5 (a) and the time-domain plot in Figure 6.5 (b). The 0.14 W sensor has a higher reflectivity compared with the 0.12 W sensor due to the higher femtosecond laser fabrication power. The 0.12 W sensor was left free to hang and strains of $82 \mu\epsilon$ and $163.4 \mu\epsilon$ applied in a similar manner to the previous strain test, while the 0.14 W sensor was fixed on the optical bench with no additional strain applied over the course of the test. The resulting frequency domain interferograms of the 0.12 W sensor and the 0.14 W sensor are shown in Figure 6.5 (c) and (d). With strain applied, a clear frequency domain interferogram shift trend was observed with the 0.12 W sensor; during that time, no shift was observed in the interferograms of the 0.14 W sensor to which no additional strain was applied, indicating good multiplexing capability. Of note, ideally the frequency domain interferogram of periodic grating structures should contain only one strong peak within each resonance period. This was not true of the 0.14 W THz FBG; the authors surmise that this lack of a clear peak was the result of imperfections introduced during fabrication. The precise mechanism of this lack of a clear peak for this particular 0.14 W THz FBG will be the subject of future research; however, this lack did not prevent the authors from observing frequency shifts during testing, as evidenced in Figure 6.5 (d).

Although the chirp-DFB lasers are a suitable method of interrogating THz FBGs, they present several limitations. The maximum interrogation range in the frequency domain is limited by the sweep bandwidth of the chirp-DFB laser, which is approximately 100 GHz; consequently, large strain changes with frequency shifts greater than 100 GHz cannot be resolved. Additionally, the precise starting optical frequency for each frequency sweep may vary; a calibration method that precisely tunes the starting frequency will be investigated in subsequent work. Although the intensity output of laser does vary due to the current injection modulation, the fact that changing output intensity did not prevent the interrogation to measure multiplexed strain changes using THz FBGs. Optical or electrical automatic gain control module can be added to potentially solve this problem for particular applications.

Conclusions

To conclude, this letter reports a chirped DFB laser-based interrogator for THz FBGs. A DFB laser with current injection modulation was employed as the frequency sweep source used to interrogate two THz FBGs. A feedback iteration method and an auxiliary clock were applied to increase the sweep linearity. 110 GHz interrogation bandwidth within 1 ms was achieved. Strain testing and multiplexing testing were conducted to experimentally investigate the system. The results of these tests demonstrate that this system holds substantial potential as a method of dynamic distributed strain sensing, particularly for applications in which increased sampling speed is of particular benefit.

7. Digitally controlled chirped pulse laser for sub-terahertz-range fiber structure
interrogation

by

Zhen Chen, Gerald Heffernan and Tao Wei

published in

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Abstract

This letter reports a sweep velocity-locked laser pulse generator (SV-LLPG) controlled using a digital phase locked loop (DPLL) circuit. This design is used for the interrogation of sub-terahertz-range fiber structures for sensing applications that require real-time data collection with mm-level spatial resolution. A distributed feedback laser (DFB) was employed to generate chirped laser pulses via injection current modulation. A DPLL circuit was developed to lock the optical frequency sweep velocity. A high-quality linearly chirped laser pulse with a frequency excursion of 117.69 GHz at optical communication band was demonstrated. The system was further adopted to interrogate a continuously distributed sub-THz-range fiber structure (Sub-THz-FS) for sensing applications. A strain test was conducted in which the Sub-THz-FS showed a linear response to longitudinal strain change with predicted sensitivity. Additionally, temperature testing was conducted in which a heat source was used to generate a temperature distribution along the fiber structure to demonstrate its distributed sensing capability. A Gaussian temperature profile was measured using the described system and tracked in real-time as the heat source was moved.

Introduction

Sub-terahertz-range fiber structures (sub-THz-FS) have demonstrated their feasibility for distributed strain and temperature sensing applications [24, 44, 64, 71]. By definition, a sub-THz-FS is an optical fiber-inline structure with characteristic geometries in the millimeter or sub-millimeter range that can be interrogated using sub-THz bandwidths in the optical frequency band[74]. Uniquely, sub-THz-FSs allow systems to simultaneously achieve distributed strain and temperature measurements with high-accuracy and high

spatial resolution using a narrow interrogation bandwidth. Previously, the interrogation system of sub-THz-FSSs was based on coherent optical frequency domain reflectometry (C-OFDR) technique where the key component was a highly coherent swept laser source, specifically, an external cavity tunable laser (ECL). An ECL tunes its lasing wavelength via modulating the physical length of an externally-coupled cavity. Recent progress in micro-electro-mechanical systems (MEMS) technologies has led to miniaturized ECLs that can be as compact as conventional semiconductors [77]. The unique advantage of ECLs include high coherence length and mode-hop-free broadband tuning (>100 nm or >12.5 THz at the 1.55 μm band). Their disadvantages include inconsistent sweep velocity, non-repeatable starting wavelength, high system complexity with geometrically coupled moving optical components, and high cost. Several additional components are used to compensate for these limitations: an auxiliary sampling clock (k-clock) is employed to accommodate nonlinear sweep speeds and a wavelength reference gas cell is used to calibrate starting wavelength [66, 78]. Although effective, these methods add complexity, cost, and increased device footprint to ECLs.

In contrast, a distributed feedback laser (DBF) is also capable of mode-hop-free wavelength tuning via modulating its injection current, without the need for moving geometric-optic components. However, there are two critical fundamental challenges associated with using this frequency sweep technique for C-OFDR-based applications: (1) a limited tuning bandwidth (~ 100 GHz), and (2) a nonlinear relationship between injection current and laser frequency, leading to inconsistent sweep velocities. The challenge of limited bandwidth, which restricts the spatial resolution of many C-OFDR applications, is readily overcome using sub-THz-FSSs due to their unique, proven ability to facilitate narrow

interrogation bandwidth operation [24, 44, 74]. Thus, inconsistent sweep velocity represents the key remaining challenge precluding the use of tunable DFB lasers for sub-THz-FS sensor interrogation. Efforts have been made to overcome this remaining limitation by implementing an auxiliary sampling clock; however, due to the Nyquist criterion, the delay line for the interferometer used in the sampling clock must be at least four times longer than the total length of sensing arm. This long delay line makes the interrogation system more susceptible to ambient noise, and, given the same sweep velocity, necessitates the use of high frequency electronics, resulting in increased design complexity and system cost.

This letter described an alternative approach that actively linearizes the frequency sweep in order to overcome the remaining challenge of inconsistent sweep velocity directly, allowing for purely-electronically modulated DFB lasers to be used for sub-THz-FS sensor interrogation. A sweep velocity-locked laser pulse generator (SV-LLPG) based on a digital phase locked loop (DPLL) design was theoretically developed and prototyped. Using this approach, a tuning bandwidth of 117.69 GHz was achieved over 8.3 ms. A highly consistent sweep velocity of 14.2 GHz/ms was maintained within each chirped pulse. The standard deviation of the starting frequency was measured to be 109 MHz, corresponding to a strain sensing instability of $0.75 \mu\epsilon$, or a temperature sensing instability of 0.08°C , obviating the necessity of starting frequency calibration of any kind for most applications. The SV-LLPG prototype was used to interrogate a sub-THz-FS. A linear strain response was obtained with a sensitivity of $-0.1436 \text{ GHz}/\mu\epsilon$, which agrees with previously reported results obtained using an ECL. Additionally, a soldering iron was

employed as a heat source to form a temperature distribution along a continuously cascaded sub-THz-FS array to demonstrate its high spatial resolution distributed sensing capability.

Operation Mechanism

Figure 7.1 Schematic of the proposed Sub-THz-FS interrogation system using SV-LLPG. (ADC: analog-to-digital converter, DSP: digital signal processing unit, MZI: Mach-Zehnder Interferometer, AGC: automatic gain control amplifier.)

A schematic of the described interrogation system is shown in Figure 7.1. A DFB laser serves as the laser source, which is modulated using a time-varying voltage signal through a laser driver circuit. An isolator is placed at the output of the laser to eliminate reflection. Using a 90/10 coupler (CPL), 10% of the power is directed into a fixed MZI to monitor sweep speed, while 90% of the remaining power is sent into the sensing module (upper part of Figure 7.1) to activate and interrogate the sub-THz-FSs. The MZI has a fixed delay, τ_d , of 10.58 ns. Under the assumption that the DFB laser is operated with an ideal constant sweep velocity, the AC-coupled current output of the photo diode after the MZI as a function of time, $i(t)$, can be expressed as:

$$i(t) = \frac{A(t)^2}{8} \eta \cos[2\pi(f_0 + vt)\tau_d]$$

where $A(t)$ is the amplitude of the electric field directed into the MZI as a function of time, η is the light-to-voltage conversion coefficient of the photodiode, f_0 is the starting

Figure 7.2 Spectrogram of AGC output within a chirped laser pulse: (a) free running; (b) sweep velocity locked; (c) modulation waveforms when the laser sweep velocity is locked.

frequency of the DFB laser sweep, v is the optical frequency sweep velocity, and t is time. Light passing through the MZI generates a beat frequency in the radio frequency (RF) range, which is linearly proportional to the optical frequency sweep velocity given a fixed MZI delay, τ_d . Due to the current injection modulation, the intensity of the DFB laser output varies as a function of time. To account for this effect, an automatic gain control (AGC) transimpedance amplifier is used to adjust the amplitude of the AC-coupled signal output of the photodiode. A voltage comparator is used to convert the analog beat signals generated by the MZI into digital signals, which are then compared to a high-quality digital reference clock with a frequency, f_R , of 150 kHz. Phase errors are then extracted via a type

I digital phase comparator. A loop filter is used to convert the digital phase error signal into a laser control signal, which is then fed into the laser driver to complete the control loop. It is worth noting that the SV-LLPG can be considered a digital version of an optical phase locked loop (OPLL), and obviates the need for optical amplitude feedback control of analog OPLLs [72, 79]. Compared with analog mixers, digital phase comparators are inexpensive and less sensitive to noise. Additionally, no polarization maintaining devices were included in the entire system.

A spectrogram of the AGC output during a chirped laser pulse under free-running, open loop operation (when the AGC output is disconnected from the voltage comparator) is shown in Figure 7.2 (a). After closing the control loop, the output of AGC—and thus laser sweep velocity—is locked during each chirped laser pulse. When locked, the AGC is in phase with the digital reference clock; the locked optical frequency sweep velocity, v , can therefore be expressed as:

$$v = \frac{f_R}{\tau_d}$$

Given the fixed MZI delay and reference frequency, the locked sweep velocity is calculated to be ~ 14.2 GHz/ms. Figure 7.2 (b) shows the AGC output within a chirped pulse under the sweep velocity locked condition. The total locking period within a chirped pulse is ~ 8.3 ms, leading to an optical interrogation bandwidth of 117.69 GHz. Figure 7.3 (a) shows the Fourier transform of the AGC output over the span of 8.3 ms under locked condition; over that span, a signal-to-noise ratio (SNR) above 50 dB was achieved. During testing, a resting period of 5 ms followed each 9 ms sweep in order to discharge the capacitors in the loop filter, resulting in a total 14 ms for each complete pulse cycle and a repetition rate of 71 Hz. To determine the noise of the system, 1 second of data with 71

chirped laser pulses was recorded. The Fourier transform of this data is plotted in Figure 7.3 (b). A 71 Hz frequency period was observed due to the repetition rate. The full width at half maximum (FWHM) of the peak envelope using a Gaussian curve fit was measured to be 116 Hz.

A homodyne configuration was constructed using two 2×2 3-dB couplers, depicted in the sensing module of Figure 7.1. The input light is split into two paths via the first coupler, with one path serving as the reference arm and the other path directed into the sensing arm including a sub-THz-FS array. The sensing arm was terminated using an anti-reflection cut. The reflected light from sub-THz-FSs was then combined with light from the reference arm through the second coupler. A photodetector and a single channel AC-coupled 12-bit ADC was used to record the resulting data. The sampling rate of the ADC was set to 8 MSa/s with a matched anti-aliasing filter. The digitized raw data was then fed into a DSP module.

Figure 7.3 Quality of sweep velocity locking: (a) Fourier transform of the AGC output over the locked span of 8.3 ms; (b) a Gaussian curve fit applied to the measure the FWHM of the Fourier transform of a chirped pulse train over 1 second.

Experimental Results and Discussions

In order to investigate the sensing capability of the described concept, a 20-pt periodic weak reflection sub-THz-FS array with a 1 mm pitch length was fabricated along a single mode fiber (SMF-28, Corning, Inc.) using a Ti: Sapphire femtosecond laser (Coherent, Inc.) [26, 38]. During interrogation and signal processing, the sub-THz-FS array was considered as 9 cascaded sub-THz-grating sensor units using a 4-mm wide moving Butterworth bandpass filter with a step size of 2-mm. In this case, each sensor unit contains 4 reflection peaks. This signal processing method has been systematically investigated in the previous publications [24, 44, 74]. The interferograms of the target sensor units were extracted using a self-mixing method and a low-pass filter. Changes in strain or

Figure 7.4 Static strain test: (a) time domain reflections of DUT; (b) interferograms of the sensor unit between 3975 mm and 3979 mm with varied strain applied; (c) strain test results for all 9 sensor units; (d) strain test results for 8th sensor unit

temperature along the optical fiber result in optical path length (OPL) changes between the weak reflectors of the sub-THz-FS array. Thus, a phase-shift in the resulting interferogram can be used to measure strain and temperature along the sensor probe.

Figure 7.5 Distributed temperature test: (a) schematic; (b), (c) testing results [Visualization 1]

To demonstrate the strain sensing capability of the system, a series of static strain tests were conducted. One end of the device under test (DUT) was secured to an optical bench while the other end was left free to hang. Weights were sequentially added to the free end of the fiber at 1.33 g intervals; in total 7.98 g of weights were added to the free end of the DUT, resulting in a strain change of $93.92 \mu\epsilon$. The SV-LLPG system was set using the parameters described above, resulting in a total sweeping bandwidth of 117.69 GHz. The resulting distance domain signals, calculated using a Fourier transform and in which the sensor structures can be identified between 3969 mm and 3989 mm, are plotted in Figure 7.4 (a). The individual reflection peaks of the sub-THz-FS array elements cannot be resolved due to the narrow bandwidth used for interrogation. The measured frequency domain interferograms of the 3rd sensor unit between 3975 mm and 3979 mm are plotted in Figure 7.4 (b). The strain test results for all 9 sensor units are plotted in Figure 7.4 (c), and

the results of the 8th sensor unit specifically are plotted in Figure 7.4 (d). Linear results were observed for all sensor units, with the least linear having a R2 value of 0.9950. The mean strain sensitivity across all sensing elements was calculated to be $-0.1436 \text{ GHz}/\mu\epsilon$ with a standard deviation of $0.0078 \text{ GHz}/\mu\epsilon$. A stability test was conducted in which the sub-THz-FS array was affixed to an optical bench and no strain changes applied. 100 groups of measurements were collected; the maximum standard deviation among these sensor units was calculated to be 0.16 GHz, corresponding to a detection limit of $1.11 \mu\epsilon$. The starting sweep frequency was evaluated by measuring the starting frequency of the entire system over 1000 captures, and the standard deviation of start frequency was 109 MHz.

In order to demonstrate the distributed sensing capability of the system, a dynamic temperature test was conducted. A schematic illustration of the testing setup is shown in Figure 7.5 (a). The interrogator setup was identical to that of the static strain test. A heat source (a soldering iron tip heated to 400 °F) was then placed approximately 2 mm from the sub-THz-FS array. The heat source was free to move along the direction of the array in order to introduce a changing temperature distribution at various locations along the optical fiber. A graphical unit interface (GUI) was employed to generate temperature profile along the Sub-THz-FS array in real-time at a refresh rate of 2.5 Hz. Figure 7.5 (b) and (c) show the measured temperature distributions with the heat source at different locations. A video file documenting this distributed temperature testing is included as a supplement to this manuscript.

Conclusions

To conclude, this manuscript reports a SV-LLPG enabled by a DPLL circuit to interrogate a sub-THz-FS sensor array for distributed sensing with millimeter-level spatial resolutions. A highly linearly chirped pulse over a bandwidth of 117.69 GHz at optical frequency was achieved within 8.3 ms at a repetition rate of 71 Hz. The locked sweep velocity was 14.2 GHz/ms. The proposed apparatus was built around a purely electronically-modulated DFB laser source. A static strain test was conducted and linear results observed, with a mean sensitivity of $-0.1436 \text{ GHz}/\mu\epsilon$ and a detection limit of $1.11 \mu\epsilon$. In order to evaluate the distributed sensing capability of the system, a dynamic temperature sensing test was conducted, which demonstrated the system's ability to measure changing temperature distributions in real-time. This system holds substantial potential as a means of achieving rapid, real-time measurement of distributed temperature and strain data for a broad range of sensing applications.

8. Field-programmable gate array-controlled sweep velocity-locked laser pulse generator

by

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Abstract

This manuscript reports a FPGA-controlled sweep velocity-locked laser pulse generator (SV-LLPG) design based on an all-digital phase-locked loop (ADPLL). A distributed feedback (DFB) laser with modulated injection current was used as a swept-frequency laser source. An open loop pre-distortion modulation waveform was calibrated using a feedback iteration method to initially improve frequency sweep linearity. An ADPLL control system was then implemented using a field programmed gate array (FPGA) to lock the output of a Mach–Zehnder interferometer that was directly proportional to laser sweep velocity to an on-board system clock. Using this system, linearly chirped laser pulses with a sweep bandwidth of 111.16 GHz were demonstrated. Further testing evaluating the sensing utility of the system was conducted. In this test, the SV-LLPG served as the swept laser source of an optical frequency domain reflectometry (OFDR) system was used to interrogate a sub-terahertz range fiber structure (sub-THz-FS) array. A static strain test was then conducted and linear sensor results were observed.

Introduction

Frequency modulated continuous wave (FMCW) reflectometry or optical frequency domain reflectometry (OFDR) [2, 5, 54], is a well-established frequency domain measurement method for optical component characterization and optical fiber distributed sensing. This technique allows distance domain information to be obtained from frequency domain intensity data via a Fourier transform. A key component of this FMCW reflectometry system is a swept-frequency laser source. A variety of laser sources have been investigated for this purpose, including temperature and piezo-electrically tuned Nd: YAG ring lasers [67, 68], external cavity lasers (ECLs) [24, 25,

44, 80, 81], piezo-electrically tuned fiber grating lasers [70], and chirped distributed feedback (DFB) lasers [69].

Among these sources, the chirped DFB laser represents a particularly promising candidate for narrow-bandwidth interrogation applications. The output frequency of DFB lasers can be controlled using injection current modulation without the need for any moving mechanical components, resulting in a fast repetition rate over a sweeping bandwidth of ~ 100 GHz. Other beneficial features of chirped DFB lasers include single longitudinal mode output, good laser coherence length ($\sim$ km), and low cost. However, there are several drawbacks limiting chirped DFB lasers as elements of FMCW/OFDR systems. Chief among these is a non-linear relationship between input current and output frequency, leading to non-linear optical sweep speeds. To compensate this non-linearity, a pre-distortion waveform can be generated based on a feedback iteration method [82]. However, this method only fractionally enhances the linearity of the resulting optical sweep speed. An auxiliary clock or ‘k-clock’ with a fixed optical delay can also be applied to resample the data and correct for non-linear sweep speeds [82]. However, this sampling clock method increases both system sampling and signal processing complexity.

A closed loop control system based on an optical phase-locked loop (OPLL) that modifies laser output frequency in real-time offers an alternative approach to precisely controlling optical sweep speed [72, 83]. Recently, a digital-controlled chirped pulse laser based on a digital phase-locked loop (DPLL) design was reported based on modular electronic design [84]. A digital phase comparator (XOR gate) was utilized to extract phase errors between the output of a Mach-Zehnder interferometer, which

converted laser sweep speed to a radio-frequency signal, and a reference oscillator. The system generated a highly linear frequency sweep, and its utility as a source for high spatial resolution fiber sensing applications was demonstrated. However, while this system successfully demonstrated the concept, there remain engineering challenges, stemming from the fact that analog systems are susceptible to noise and DC drifts in comparison to similar digital systems [85, 86]. More importantly, modular design results in relatively high power consumption, large size and weight of the final product.

This manuscript reports an alternative design for a sweep velocity-locked laser pulse generator (SV-LLPG) using an all-digital phase-lock loop (ADPLL), which has the potential to surmount several of the previous engineering challenges facing modular DPLL design. The ADPLL is constructed such that all components, including the phase comparator, loop controller, and reference frequency synthesizer, are digitally generated using logic gates and integrated in an IC chip. This design was then implemented using a field-programmable gate array (FPGA) in which all digital components were synchronized using the same on-chip clock to minimize phase noise. The FPGA chip used in this design is from Xilinx Zynq 7000 series, and the DAC is a Texas Instruments DAC121S101 with 12-bit resolution and a sampling rate of 1 MSa/s. Using this approach, a sweeping bandwidth of 111.16 GHz over 9 ms has been demonstrated. A highly consistent sweep velocity of 12.35 GHz/ms is maintained within each chirped pulse. The standard deviation of the starting frequency was measured to be 106.7 MHz, corresponding to a strain sensing instability of $0.79 \mu\epsilon$. In order to evaluate the potential of the ADPLL-based SV-LLPG as an element of an OFDR system, the system was used to interrogate a sub-THz-FS array. Highly linear results and a sensitivity of -0.1346

GHz/ $\mu\epsilon$ were observed, which agrees well with previously reported sensing results obtained using an ECL [24, 44].

Operation Mechanism

Figure 8.1 Schematic of proposed all-digital OPLL system with sensing module and control module (MZI: Mach-Zehnder interferometer; FPGA: field-programmable logic array; DAC: digital-to-analog converter; ADD: adder; PRE: pre-distortion curve; LC: loop controller; REF: reference frequency clock; PD: type-II phase detector; ADC: analog-to-digital converter; DSP: digital signal processing unit).

A schematic of the described interrogation system is shown in Figure 8.1. In the SV-LLPG module, a DFB laser is employed as the frequency sweep source, which is injection current-modulated using a time-varying voltage via a laser control circuit. An isolator is placed at the laser output to eliminate reflection. Using a 90/10 coupler, 10% of the output power is directed in to the MZI and 90% of the power into the sensing module to interrogate the sub-THz-FS array. The MZI is constructed with two 3-dB couplers with a constant delay, τ_d , of 11.334 ns. Under the assumption that the DFB laser is operated at a constant sweep velocity, the AC-coupled current output $i(t)$ at the photo diode after the MZI as a function of time can be expressed as:

$$i(t) = \frac{A(t)^2}{8} \eta \cos[2\pi(f_0 + vt)\tau_d]$$

where $A(t)$ is the electrical-field amplitude directed into the MZI as a function of time, η is the responsivity of the photo diode, f_0 is the initial frequency of the DFB laser during sweeping, v is the optical sweep velocity, and t is the time. A beat frequency in the radio frequency (RF) range less than 250 kHz, which is linearly proportional to laser sweep velocity, is generated through this fixed delay MZI. Due to the current injection modulation, the intensity of the DFB laser output varies as a function of time. To account for this effect, an automatic gain control (AGC) transimpedance amplifier is used to adjust the amplitude of AC-coupled photodiode output signal. This photodiode has a bandwidth of 1MHz. A high-speed voltage comparator with a bandwidth of 50 MHz is used to convert the analog beat signals into digital signals, which is sent into a digital input port of a FPGA evaluation board with a 100 MHz system clock. In order to improve the initial laser sweep linearity before phase locking, a pre-distortion voltage waveform is pre-calibrated using a feedback iteration method [82], resulting in an output frequency sweep velocity at about 12.5 GHz/ms. This open loop pre-distortion voltage waveform is then stored within the FPGA memory. A type-II phase comparator, constructed with two D flip-flops and an AND gate [87], is used to extract the phase difference between the input digital signal and the on-board reference frequency clock f_R at 140 kHz. The resulting phase error signals are then fed into a loop controller constructed using an integrator to further modify the pre-distortion current modulation waveform. The digital output of the FGPA is converted to an analog signal using a digital-to-analog converter (DAC) module with a refresh cycle of 1 μ s and sent to the laser driver circuit.

Figure 8.2 Measured frequency spectrum of AGC output within a chirped laser pulse: (a) free running with ramp input; (b) free running with calibrated pre-distortion input; (c) sweep velocity locked.

Spectrograms of the AGC output during a chirped laser pulse under the free-running open loop case (when the phase errors are not fed into the loop controller) with an unmodified ramp input and under the pre-calibrated modulation waveform case are shown in Figure 8.2 (a) and (b). Sweep linearity is substantially improved using the pre-distortion curve compared with the initial ramp waveform. After closing the control

loop (i.e. when the phase errors are fed into the loop controller), the laser sweep velocity is locked during each chirped laser pulse. When locked, the AGC output signal is in phase with the digital reference clock and the locked optical frequency sweep velocity v can be expressed as:

$$v = \frac{f_R}{\tau_d}$$

Given the fixed MZI delay length τ_d and the digital reference clock frequency f_R , the locked sweep velocity is calculated to be 12.35 GHz/ms. Figure 8.2 (c) shows the AGC output within a chirped pulsed under the locked condition. The total locking period within the chirped pulse is approximately 9 ms, leading to an optical sweeping bandwidth of 111.16 GHz. Figure 8.3 (a) shows the Fourier transform of the AGC output over the span of 9 ms under the locked condition; over that span, a signal-to-noise ratio (SNR) above 35 dB was achieved. During testing, a resting period of 10 ms followed each 10 ms sweep in order discharge the capacitor within the laser driver circuit, resulting in a total period of 20 ms for each complete pulse cycle and a repetition rate of 50 Hz. The output of the chirped laser pulse generator for 5 complete cycles at the photodetector is plotted in Figure 8.3 (b). To determine the noise of the system, 1 second of data with 50 chirped laser pulses was recorded. The Fourier transform of this data is plotted in Figure 8.3 (c). A center frequency of 139.667 kHz was found. A 50 Hz frequency period was observed due to the repetition rate described above. The full width at half maximum (FWHM) of the peak envelope using a Gaussian curve fit was measured to be 90 Hz.

Figure 8.3 (a) Fourier transform of the AGC output over the locked span of 9 ms; (b) output of the laser pulse generator with 5 complete cycles; (c) a Gaussian curve fit applied to measure the FWHM of the Fourier transform of a chirped pulse train over 1 second.

Along the sensing module, a homodyne interferometry structure is constructed using two 2×2 3-dB couplers as shown in Figure 8.1. The input light is split into two paths via the first coupler, with one serving as reference arm and the other path directed into the sensing arm, which includes a sub-THz-FS array. The sensing arm is terminated using an anti-reflection cut. The reflected light from the sub-THz-FS is then combined with light from reference arm via the second coupler. A photodetector and a single channel AC-coupled 8-bit analog-to-digital converter (ADC) is used to record the resulting data. The sampling rate of the ADC is set to 8 MSa/s with a match anti-aliasing filter. The digitized raw data is then fed into a DSP module.

Experimental Results and Discussions

Figure 8.4 Static strain test: (a) time domain reflections of DUT; (b) interferograms of the sensor unit between 1779 mm and 1783 mm with varied strain applied; (c) strain test results for all 9 sensor units; (d) strain test results of for 7th sensor unit.

In order to investigate the sensing capability of the described SV-LLPG system, a 20-pt periodic weak reflection sub-THz-FS array with a 1 mm pitch length was fabricated along a single mode fiber (SMF-28, Corning, Inc.) using a Ti: Sapphire femtosecond laser micromachining system (Coherent, Inc.) [24, 44, 64, 73]. During interrogation and signal processing, this sub-THz-FS array was considered to be 9 cascaded sub-THz- grating sensor units using a 4-mm wide moving Butterworth bandpass filter with a step size of 2-mm. Each sensor unit contains 4 reflection peaks. This signal processing method has been systematically investigated in the previous publications (7, 22). A self-mixing method and a low pass filter is applied to extract the resulting interferograms. Changes in strain along the optical fiber result in optical path length (OPL) changes between the weak reflectors, which generate a phase-shift in the interferograms that are used to measure strain changes along the sensor probe.

To evaluate the strain sensing capability of the system, a series of static strain tests were conducted. One end of the fiber under test (FUT) was secured to an optical bench while the other end was left free to hang. Weights were sequentially added to the free

end of the fiber at 1.33 g intervals; in total 10.64 g of weights were added to the free end of the FUT, resulting in a strain change of 125.23 $\mu\epsilon$. The SV-LLPG system was set using the parameters described above, resulting in a total sweeping bandwidth of 111.16 GHz. The resulting distance domain signals, calculated using a Fourier transform and in which the sensor structures can be identified between 2047 mm and 2067 mm, are plotted in Figure 8.4 (a). Due to the limited interrogation bandwidth, the individual reflection peaks of the sub-THz-FS array elements cannot be resolved. The measured frequency domain interferograms of the 7th sensor unit between 2059 mm and 2063 mm are plotted in Figure 8.4 (b). The strain test results for all 9 sensor units are plotted in Figure 8.4 (c), and the results of the 7th sensor unit specifically are plotted in Figure 8.4 (d). Linear results were observed for all sensor units, with the least linear having a R^2 value of 0.9986. The mean strain sensitivity across all sensing elements was calculated to be -0.1346 GHz/ $\mu\epsilon$ with a standard deviation of 0.0026 $\mu\epsilon$. The start sweep frequency was evaluated by measuring the starting frequency of the entire system over 1000 captures, and the standard deviation of start frequency was 106.7 MHz.

Conclusions

To conclude, this manuscript reports a FPGA-controlled sweep velocity-locked laser pulse generator (SV-LLPG) design. A DFB laser is employed as the sweep source and an ADPLL control system is used to lock the laser sweep velocity to an on-board reference clock. Highly linear chirped laser pulses with a bandwidth of 111.16 GHz were demonstrated. A sweep velocity of 12.35 GHz/ms was achieved for 9 ms within each chirped pulse at a 50 Hz pulse repetition rate. To investigate system sensing utility, the SV-LLPG prototype was used as an element of an OFDR system to interrogate a

sub-THz-FS array. A static strain test was conducted and highly linear results were observed.

The proposed device holds the promise to deliver a low size, weight and power (SWaP) and affordable interrogator for distributed fiber sensing applications. In addition, the FPGA based design makes it easier to be integrated and adopted for various applications in the future.

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