A MICROMACHINED PLATFORM FOR LOCALIZED INDEX MODULATION IN CHIRPED FIBER BRAGG GRATINGS AND ITS APPLICATION TO ULTRAFAST OPTICAL PULSE SHAPING

Kabir Udeshi[1*], Kai-Hsiu Liao[†], Long Que[†], Almantas Galvanauskas[†] and Yogesh B. Gianchandani[*†]
[†]*Department of Electrical Engineering and Computer Science,*
[*]*Department of Mechanical Engineering,*
University of Michigan, Ann Arbor, USA

ABSTRACT

This paper reports the development of a micromachined platform that locally modifies the refractive index of a chirped fiber Bragg grating (CFBG). This platform, composed of an array of electrothermal actuators, has been used to make an ultrashort optical pulse shaper. The micromachined array, with a footprint of 5 mm x 1 mm, has 75 actuators spaced 60 µm apart, and has been used to demonstrate pulse shaping both in the time and frequency domain. A normalized intensity peak of 1.5 at 1550 nm is obtained by applying about 2 mN of force using a single actuator. The intensity peak can be shifted by over 3 nm to the edge of the CFBG spectrum by using different actuators. The pulse width is modulated from 1.5 ps to 4 ps by application of 500 mW of power. System simulations track experimental data that show the individual actuators addressing distinct frequency components. Thermal experiments verify that heat generated by the electrothermal actuators has no measurable effect on the optical pulse spectrum obtained.

I. INTRODUCTION

Ultrashort pulse shaping has a variety of applications such as coherent control of chemical reactions, nonlinear optics, dispersion compensation and optical communications [1]. Traditional pulse shapers use a diffraction grating and a lens to separate light into its spectral components [2]. This Fourier transformed light is passed through a spatial light modulator (SLM), such as a mask, to modify the amplitude and phase of the desired frequency components, and then recombined using another diffraction grating, lens pair. The drawback of this method is that a unique mask needs to be fabricated for every pulse shape desired. In order to overcome this limitation liquid crystal SLMs were developed to allow dynamic programmable modification on a millisecond time scale. Other methods to carry out programmable pulse shaping include the use of acoustic-optical modulators, and movable deformable and micromachined mirrors. Each of these methods has their own advantages and limitations; the common feature being that they have table-sized setups, require optical alignment, which is extremely time consuming besides being tedious, and much care must be taken to avoid dispersion effects due to light propagation through lenses. The need for delicate optical equipment and the overall dimensions of the setup make pulse shaping using SLMs neither portable nor robust and require skilled personnel for operation in a laboratory environment.

This paper reports on an effort to perform variable pulse shaping by using electrothermal actuators [3-5] to tune a chirped fiber Bragg grating (CFGB). It is well known that the refractive index of glass is modified by strain [6]. Through the use of micromachined actuators, a precisely controlled force may be applied on glass [7], resulting in a localized strain profile, hence changing its refractive index. This paper demonstrates the ability to selectively modify the refractive index of glass and the application of this principle to make an ultrashort optical pulse shaper.

Section II describes the principle of operation of the device that uses controlled forces generated by micromachined actuators to selectively modify the refractive index of a CFBG. The next section describes the analysis carried out, followed by the fabrication process used to make the actuator array, consisting of 75 actuators. Then experimental results are presented that demonstrate

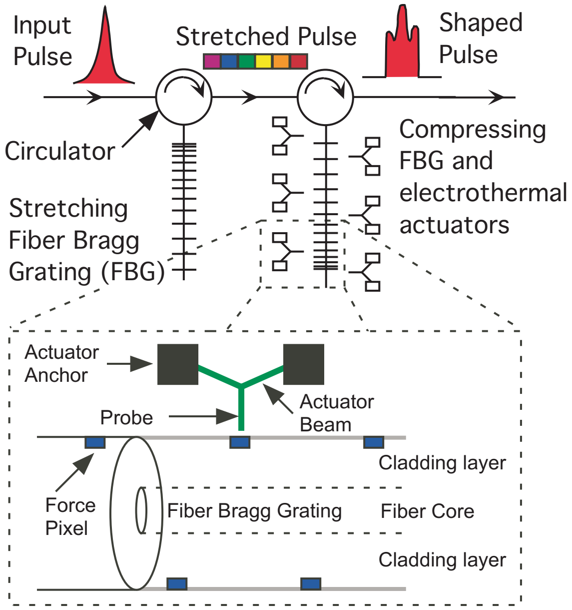

Fig. 1: An array of electrothermal actuators that behave as force pixels, locally altering the refractive index of a fiber Bragg grating, hence addressing individual components of the spectrum stretched along the length of the grating.

---

[1] *Corresponding author:* 1301 Beal Ave., Ann Arbor, MI, USA; Tel: (734) 615-7136, Fax: (734) 262-1267, E-mail: kudeshi@umich.edu

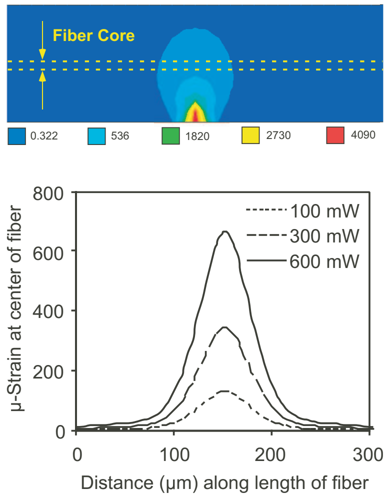

Fig. 2a: Finite element simulations indicate that the use of micromachined actuators results in a highly localized strain profile along the length of the fiber core, giving high selectivity over the spectrum being addressed.

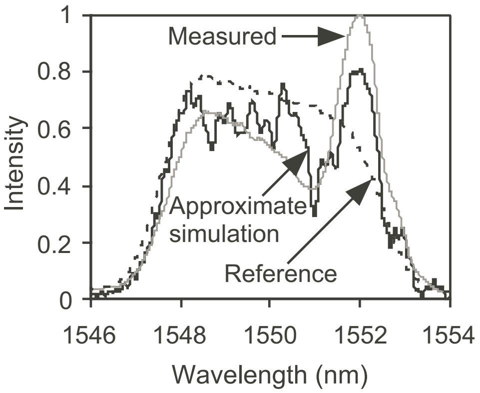

Fig. 2b: The fiber strain is used to determine the expected shift in optical spectrum, which closely matches experimental data.

pulse shaping in the frequency and time domain, followed by concluding remarks.

II. SYSTEM OPERATION

The system consists of a pair of CFBGs connected through optical circulators, one of which is inserted in a groove created between an array of electrothermal actuators.

Fiber Bragg gratings operate on the principle of Bragg reflection. When light propagates through alternating regions of higher and lower refractive index, a portion of the light is reflected at each interface. If the spacing between the interfaces is designed to be such that the partially reflected light constructively interferes, then the total reflection will add up to be nearly 100 % for a particular wavelength. The condition for high reflection is called the Bragg condition, which the wavelength reflected must satisfy: $\lambda_B = 2n\Lambda(z)$, where λ_B is the wavelength reflected at position z, $\Lambda(z)$ is the local grating period and n is the effective refractive index for the propagating mode in the fiber core [Kas99]. In order to reflect a spectrum of wavelengths as opposed to a single wavelength, the spacing between the interfaces is made to linearly vary along the length of the fiber and is said to have a "chirped profile". This chirped fiber Bragg grating (CFBG) results in the various wavelengths of light within a selected bandwidth being reflected at different positions along the length of the grating.

By using an electrothermal actuator, a localized and controlled amount of force may be applied on a CFBG (Fig. 1). This applied force results in compressive strain that locally modifies the refractive index of the grating and thus, the Bragg wavelength reflected in this region. By altering the force applied by an electrothermal actuator, the optical spectrum of the reflected pulse can be dynamically changed. In addition to this, the use of an array of actuators, a number of spectral components can be individually addressed along the length of the CFBG.

The ultrafast optical pulse shaper (Fig. 1) uses two CFBGs, one that stretches and the other that compresses an optical pulse. The array of actuators modifies the spectrum of the pulse reflected by the compressive grating and hence its shape in the time domain. This allows dynamic, programmable control over the pulse shape by addressing a range of spectral components through individual actuators.

III. ANALYSIS

The performance of the system can be modeled by a combination of mechanical and optical analyses. The strain on a fiber exerted by an actuator is determined, which is used to find the shift in optical spectrum.

The force applied by the actuator at various power levels is obtained from a three-dimensional thermo-mechanical FEA. This force is then used to obtain the strain profile at the fiber core (Fig 2a) by a second two-dimensional FEA, assuming a plane strain condition. The plane strain assumption is valid as the area of interest is the fiber core, with a diameter of about 10 μm, is about ten

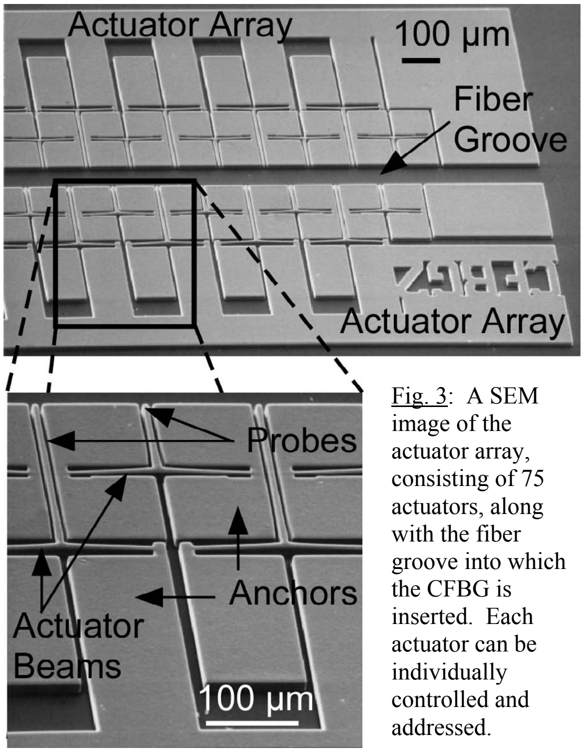

Fig. 3: A SEM image of the actuator array, consisting of 75 actuators, along with the fiber groove into which the CFBG is inserted. Each actuator can be individually controlled and addressed.

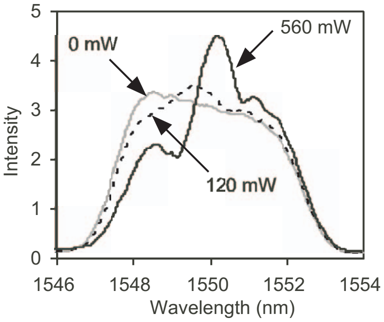

Fig 4: Changes in spectral response for various levels of input power applied to a single electrothermal actuator.

times smaller than the overall diameter of the fiber. A laterally confined strain profile, with a full-width-at-half-maximum (FWHM) of less than 80 µm gives adequate control over the spectral component addressed by a given actuator as shown through experimental results. The maximum force exerted by an actuator is estimated to be in about 2 mN. These large forces can be obtained as the actuators have a negligible displacement, being in contact with the CFBG even before power is applied [6].

The strain profile and the acousto-optic coefficient of fused silica are used to obtain the change of the reflective index of the fiber. This is used to calculate the effective-index of each region of the CFBG at different wavelengths [8]. After the effective-indices are acquired, the effect of each region is cascaded to get the composite response for different wavelengths.

The measured and the simulated frequency responses are shown in Fig 2b. The oscillating pattern of the simulated curve is due a simplified step-wise model of the grating index. The actual gratings used in the experiment are apodized, thus relieving the oscillating profile. Note that the reflectivity is shifted from shorter wavelengths to longer wavelengths. This is because when actuators generate strain in the fiber, the reflective index of the fiber increases, causing the Bragg condition to shift to longer wavelengths.

IV. FABRICATION & ASSEMBLY

The actuator arrays consist of a total of 75 actuators spaced at 60 µm intervals over a 5 mm x 1 mm die. The array is fabricated from doped silicon using a two-mask DRIE process. It consists of 50 µm-thick actuators with an aspect ratio of over 16, bonded to a glass substrate. The CFBG is inserted in the fiber groove between the actuator array (Fig 3). The dimensions of the groove are chosen so that the fiber fits snugly in the gap, with actuator tips touching the fiber.

V. MEASUREMENT RESULTS

Experiments were carried out to verify the operation of the pulse shaper and obtain changes in the pulse shape in both the time and frequency domain. In addition to characterizing the pulse shaper, experiments were carried out to verify that the spectral change observed is due to mechanical strain and that any effect of heat dissipation by electrothermal actuators is negligible.

To confirm the operation of the pulse shaper, the CFGB pair is connected as shown in Fig. 1. It should be noted that no optical alignment is required to setup the pulse shaper. The actuators in the array are individually addressed from 1 to 75 depending on their position along the length of the grating. The laser pulses are generated using an Er-doped mode-lock fiber laser with a power level in the 100 µW range.

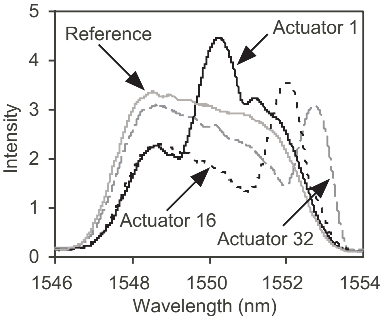

Fig 5: Changes is spectral response from various actuator locations along the length of the CFGB.

When a DC voltage is applied across an electrothermal actuator, a spectral change is observed as shown in Fig 4. By increasing the power supplied to the actuator, a more pronounced change in the spectrum is obtained. This can be explained by the fact that the actuator, when activated at higher power levels, applies a larger force. This larger force leads to an increased amount fiber strain, causing a more dramatic change in the optical spectrum.

Figure 5 shows the optical spectrum obtained by the activation of various actuators along the length of the grating. Intensity peaks are obtained for the range of optical wavelengths reflected by the CFBG through the use of different actuators.

Figure 6a shows the distinct changes in optical spectrum obtained using actuators only 240 µm apart when activated with 500 mW of power. The distinct optical spectrum obtained by the use of separate actuators serves to confirm that the spatially separated actuators are capable of addressing distinct portions of the optical spectrum. Actuators may also be simultaneously activated to obtain a combined effect on the optical spectrum as indicated by Fig. 6b. The high actuator power levels used in these

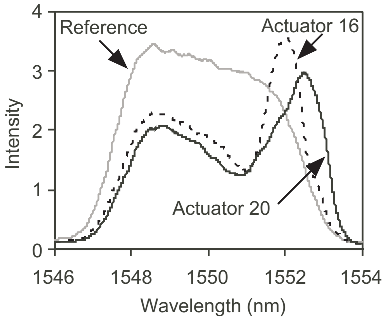

Fig. 6a: Actuators 16 and 20 have a profoundly distinct effect on the optical spectrum obtained, even though spatially separated by a distance of only 240 µm.

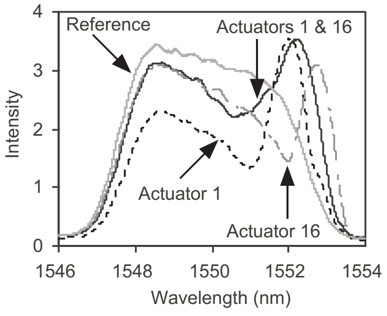

Fig. 6b: Simultaneous activation of actuators 1 & 16 causes a combined effect on the spectral response obtained.

experiments are only to demonstrate the capabilities of the system. Spectrum shifts obtained at lower actuator power may be more than sufficient for many field applications. Besides, the dimensions of the actuators and structural materials can be optimized to meet design specifications.

It is known that temperature can have a profound effect on the optical response of a CFBG [9]. It is necessary to verify that the spectral response obtained by driving the actuators is due to mechanical stress and that the effect of joule heat generated by the electrothermal actuators is negligible. A heat experiment was used to verify the claim. A needle heated to about 350 °C was brought into contact with the CFBG. This heated needle produced no appreciable change in the optical spectrum when compared to spectral changed obtained with actuators as shown in Fig. 7. In fact, the temperature at the probe tip of the actuator is estimated to be close to room temperature as most of the head generated is conducted away to the substrate.

Pulse shaping is captured in the time domain through an autocorrelation of the ultrashort optical pulse, which is the convolution of the pulse. This is only an approximate indication of the actual pulse shape. As autocorrelation captures the second harmonic using only a fraction of the optical power, the pulse is amplified to a power level of about 20 mW to account for the limits of measurement instrumentation. Figure 8 shows the output obtained through autocorrelation at various actuator power levels. The full-width-at-half-maximum (FWHM) of the optical pulses increases from 1.5 ps to over 4 ps, at higher actuator power levels, indicating that optical pulses are being shaped in the time domain as well.

The use of electrothemal actuators allows modulation of the pulse shape at a rate up to 1000 Hz, which is comparable to that obtained with liquid crystal SLMs. To obtain a higher rate of switching, electrostatic actuators may be used, while compromising on the spacing between the actuator probes.

VI. CONCLUSIONS

The micromachined actuator array, with a footprint of 5 mm x 1 mm, reported in this paper is used to locally modify the refractive index of a chirped fiber Bragg grating (CFGB). This ability is utilized to make a compact, robust and practical ultrashort optical pulse shaper. This implementation overcomes the limitations of conventional tabletop sized pulse shapers. System operation can be simulated to explain experimental observations both in the frequency and time domain. Simulations involving thermal, mechanical and optical analysis match experimental data. Thermal experiments verify that heat generated by the electrothermal actuators has a negligible effect on the optical spectrum obtained. The pulse shaper, with minor improvements, may be used in a practical application.

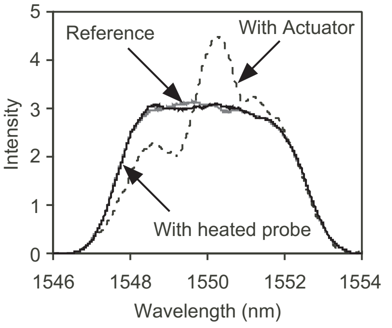

Fig 7: Heat dissipated by an electrothermal actuator has no appreciable effect on the optical spectrum obtained.

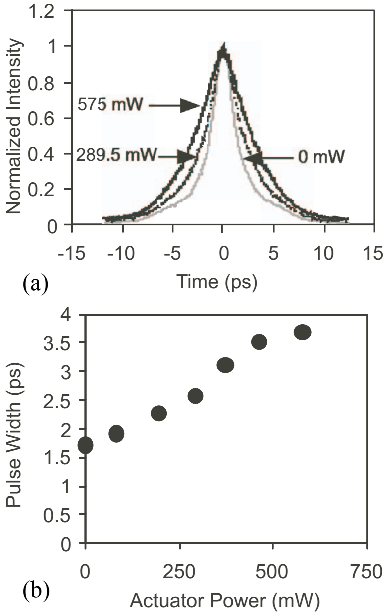

Fig 8: Autocorrelation shows a change in the pulse shape in the time domain. The width of the pulse changes from 1.5 ps to about 4 ps with the application of about 500 mW of actuator power. The normalized intensity is shown in a (upper), whereas the dependence on actuator power is shown in b (lower).

ACKNOWLEDGEMENTS

This work was partially supported by the NSF Physics Frontier Center FOCUS at the University of Michigan, Ann Arbor and University of Texas, Austin. Facilities used for this research include the Solid-State Electronics Laboratory (SSEL) at the University of Michigan. The authors would like to thank Dr. Shamus McNamara for assistance in fabrication.

REFERENCES

[1] A. Weiner, “Femtosecond optical pulse shaping and processing,” *Prog Quant Electr*, 1995, v 19, p 161-273

[2] A. Weiner, “Femtosecond pulse shaping using spatial light modulators,” *Rev Sci Instrum*, v 71, n 5, May 2000, p 1929-1960

[3] L. Que, J. Park, Y. Gianchandani, “Bent-Beam Electro-Thermal Actuators for High Force Applications,” *Proc. of IEEE MEMS*, 1999, p 31-36

[4] L. Que, J. Park, Y. Gianchandani, “Bent-beam electrothermal actuators-Part I: Single beam and cascaded devices,” *J Microelectromech S*, v 10, n 2, 2001, p 247-254

[5] J. Park, L. Chu, A. Oliver, Y. Gianchandani, “Bent-beam electrothermal actuators-Part II: Linear and rotary microengines,” *J Microelectromech S*, v 10, n 2, 2001, p 255-262

[6] P. Gianino, B. Bendow, “Calculations of stress-induced changes in the traverse refractive-index of optical fibers,” *Applied Optics*, v 20 n 3, 1981, 430-434

[7] L. Chu, Y. Gianchandani, “A micromachined 2D positioner with electrothermal actuation and sub-nanometer capacitive sensing,” *J Micromech Microeng*, v 13, n 2, 2003, p 279-285

[8] K. Winick, “Effective-index method and coupled-mode theory for almost -periodic wave guide gratings: a comparison,” *Applied Optics*, v 31, n 6, 1992, p 757-764

[9] A. Kersey, T. Berkoff, “Fiber-optic Bragg-grating differential-temperature sensor,” *IEEE Photonics Technology Letters*, v 4, n 10, 1992, p 1183-1185