Monolithic fiber-grating and MEMS based devices for controllable ultrafast pulse shaping

Kai-Hsiu Liao[*a], Kabir Udeshi[b], Long Que[a], Yogesh B. Gianchandani[ab]
Almantas Galvanauskas[a]
[a]Department of Electrical Engineering and Computer Science
[b]Department of Mechanical Engineering
University of Michigan, 1301 Beal Avenue, Ann Arbor, MI 49109-2122

ABSTRACT

A new type of optical pulse shaper for arbitrary waveform generation is demonstrated, based on fiber Bragg grating and micro-electro-mechanical system (MEMS) technologies. This is an on-chip device which is compact, robust, monolithic, and programmable and can be used for a variety of applications such as higher order dispersion compensation in fiber communication links and high-energy pulse amplification.

1. INTRODUCTION

Arbitrary waveform generation is an important technology widely used in many applications such as coherent control of chemical reactions[12], quantum systems[3], optical signal processing[45], and optical sensing. The current mostly used apparatus for ultrashort arbitrary optical waveform generation is based on diffraction grating pairs[6]. The optical tabletop design and the complexity of operation made this kind of pulse shaper stay in the labs. Its limitation in processing narrow banded signal and relatively low phase shift also make it not suitable for narrow banded signal processing. On the other hand, the first monolithic programmable pulse shaper (DAZZLER[7]) has a very limited time window, which significantly reduces its usefulness in many applications.

We reported the proof-of-the-principle demonstration of an on-chip pulse shaper. This optical pulse shaper is based on chirped fiber Bragg grating (CFBG) and micro-machining technologies and it offers many important features such as programmability, compactness, and robustness; large operating time windows from picosecond to nanosecond; wide signal bandwidth choices from femtosecond broadband signal to sub-nanometer bandwidth signal used in optical communications. This device benefits from the guided nature of single mode optical fiber so that the beam quality is totally preserved during the operating process. A zero-power-consumption mode can be achieved if latching mechanism is incorporated into the actuator design. In this case, a program-and-go power-off mode can be achieved.

2. CONCEPT

The basic idea if this pulse shaper is based on mapping different frequency components of an incoming optical signal to different longitudinal spatial positions. We adopted CFBGs which longitudinally map different frequency components onto different position along the grating. In a CFBG, different frequency components are reflected at where the Bragg condition ($\lambda_B = 2n\Lambda(z)$, 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) is locally satisfied. It is well known that strain will change the refractive index of materials. We use micro-electro-thermal actuators to apply localized pressure and generating significant stress strain in the fiber core. These pressure induced strain causes the refractive index of the fiber core and, therefore, the local Bragg-wavelength to change. By shifting the effective reflecting position around, the phase relation between different frequency components and hence the shape of optical pulse become controllable (Figure 1.)

[*] liaok@umich.edu; phone 1 734 763 1233

Fiber Lasers II: Technology, Systems, and Applications, edited by L. N. Durvasula,
Andrew J. W. Brown, Johan Nilsson, Proceedings of SPIE Vol. 5709
(SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.602038

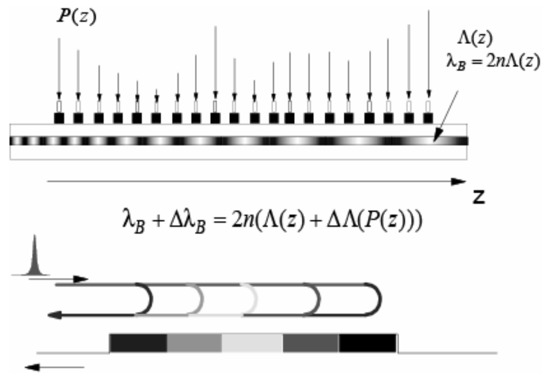

Figure 1: CFBG maps different frequency components to different effective-reflection-position where the Bragg condition is locally satisfied. By applying localized pressure, the local Bragg-wavelength and, therefore, the phase relation between different frequency components can be controlled.

3. MICRO ELECTRO-THERMAL ACTUATOR ARRAY

The micro-machined pulse shaping chip is made of silicon. Each device has and area of 5mm x 1mm and the thickness is 50 microns. As shown in Figure 2, a 80-micron wide fiber groove is in the center and as many as 75 actuators in total are lined up on both sides of the fiber groove. The 80-micron fiber groove is designed for the standard reduced cladding fiber which has a diameter of 80 microns. The standard reduced cladding fiber is chosen because a reduced distance from the fiber edge to the fiber core will significantly increase the stress strain in the fiber core when pressure is applied. According to the finite element analysis (FEA), an actuator can provide a force up to milli-Newton range which generate more than 500 micro-strain in the fiber core[8] (see Figure 3).

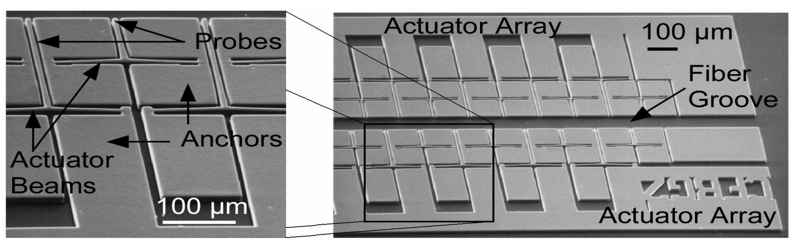

Figure 2: A scanning electron microscopy (SEM) image of the micro-fabricated actuator array and a fiber groove for 80-μm. Actuators are lined up on both sides of the fiber groove. Each actuator consists of a floated V-shaped bent-beam and a floated probe attaches to the bent-beam at the apex.

Each actuator is connected to the glass substrate through 2 large area anchors. A floating V-shaped bent-beam connects between the anchors and there is a probe stretching out from the apex of the bent-beam to the edge of the fiber groove. When current runs through the V-shaped beam, the beam heats up and expand, pushing the probe forward toward the fiber groove. If there is a piece of 80-micron fiber in the groove, it would prevent the probe from going forward and the force between the fiber and the probe tip would be huge (as high as several milli-Newton). With current device, we can generate a $\Delta\lambda \approx 0.3nm$ [9]. The force is proportional to the size of the bent-beam. By increasing the beam size, the achievable force can be increased. It is well know that the instead of strain, elevated temperature also shifts the refractive index of fused silica and therefore the frequency response of the CFBG. The two large area anchors of each actuator serve not only as supports but also good thermal conductors to dissipate heat to the glass substrate and keep the tip of the probe close to room temperature.

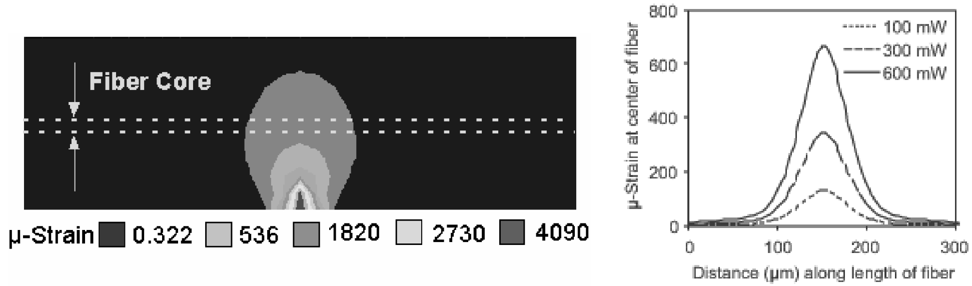

Figure 3: FEA showing strain penetration transversely and along the fiber core. In a fiber core a strain of up to hundreds of micro-strain can be created. The inter-actuator cross-talk is not significant as shown in the right plot.

4. EXPERIMENT

The measurement of this device is mainly through the spectral measurement so far. The CFBG we were using has a 50% reflectivity and a bandwidth of 4.5 nm. Amplified spontaneous emission (ASE) from an Erbium-doped amplifier is used as the source and a circulator is used to connect the input, output, and the CFBG. The result of different applied power and positions are shown in Figure 4. We can see that the frequency is both sensitive to the power driving level and the position where the pressure is applied. As shown in the figure, when a localized pressure is applied, the Bragg-wavelength of that region is shifted to the longer wavelength. Therefore, when we observe a dip in the spectrum, there is a hump in the longer wavelength. Moreover, we also conducted a simple experiment by bringing a heated probe into touch with the CFBG to make sure the results that we were observing are caused by the pressure induced Bragg-wavelength shift rather than some direct thermal effects due to the elevated temperature at the tip of the probe. The spectra were measured and shown. In Figure 4, different actuator driving power, different driving positions are shown. A comparison between an actuator and a heated probe induced spectral changes are also shown.

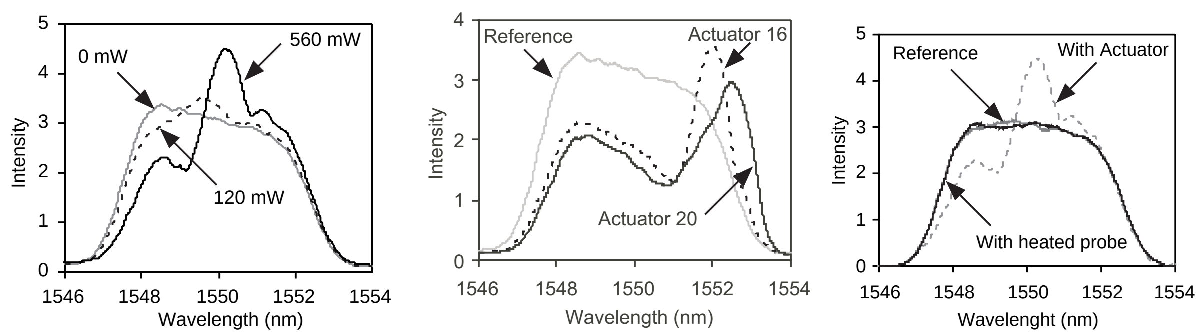

Figure 4: On the left, the spectral change of an actuator was driven at different power level is shown. In the center, two spectral changes generated by different actuator both driven at 500mW are shown. On the right, the electro-thermal actuator induced spectral change is compared to the spectral change caused by a direct heat-up of the grating using a 350 °C probe. The direct heat-up spectral change is relatively small compare to the actuator induced spectral change.

5. MODELING RESULTS

Performance of the proposed pulse shaping device is determined by a number of physically achievable critical parameters: number of control points N (number of actuators in a realistic device), maximum wavelength shift achievable with a single actuator $\Delta\lambda_{max}$, and the maximum time delay ΔT. N is associated with the complexity of obtainable shapes, $\Delta\lambda_{max}$ and ΔT relate to the maximum phase shift or, alternatively, maximum amount of dispersion (linear or higher order) achievable with a device, and ΔT is also a time window within which pulse shaper can produce non-zero output. The obtainable $\Delta\lambda_{max}$ depends on the particular type of MEMS actuator used. Our modeling of pressure actuators indicates that up to ~1000 µStrain can be achieved in the fiber core, producing up to ~1-nm of wavelength shift. This is a very large degree of phase control. Other approaches are also possible, which could provide with even larger effect on the refractive index of the core and, simultaneously, could achieve very high switching speeds. N's in 10 to 100 range are feasible, with potential further development towards ~1000 actuators in the array. Time window is determined by a grating length and for 10-cm grating it can reach ~1 ns. Example of numerically-simulated performance of such a fiber-grating/MEMS pulse-shaping device is represented in Fig. 5, where reshaped traces of initial 200-fs pulses are shown as produced by a periodic phase modulation or by various amounts of induced cubic phase. Grating in this particular example has 30-nm bandwidth at 1550nm, number of actuators in the case of periodic phase variation is 10, and in the case of induced cubic phase is 100. Limitations due to the discrete nature of the effect caused by each individual actuator are included into the model.

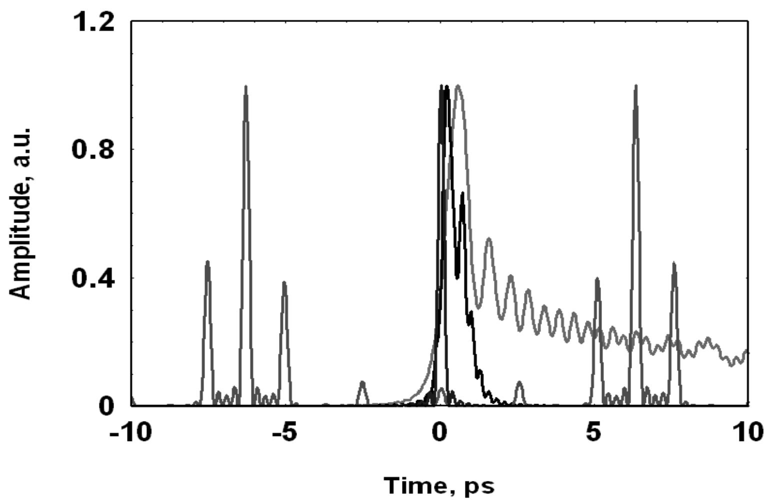

Fig. 5. Numerically simulated traces of the FBG-MEMS shaped pulses. Blue – bandwidth limited pulse, red – periodic phase modulation, black and purple – various amount of induced cubic phase.

6. CONCLUSION

We present a proof-of-the principle demonstration of a programmable arbitrary ultrashort pulse shaper, which is based on the CFBG and micro-fabrication technologies. This device is compact, robust, monolithic, and yet have large temporal and spectral operating windows which is suitable for femtoseocond broadband as well as ps signal processing. Such device is capable to compensate higher order dispersion of the optical fiber links or diffraction grating and can be programmed to fit a desired compensation needs.

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