Rapidly Reconfigurable Phase Code Generation and Recognition using Fiber Bragg Gratings

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Abstract: We demonstrate a 16-chip, 40Gchip/s, reconfigurable fiber Bragg grating based quaternary phase en/decoder with a tuning time of <2s between two different phase codes.

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1. Introduction

Optical code division multiple access (OCDMA), which combines the advantages of optical communication and access network, have the unique features of broadband, high functionality, and security [1]. One of the key technological challenges involving the OCDMA system is how to reliably achieve code generation (encoding) and recognition (decoding). The superstructure fiber Bragg grating (SSFBG) has been shown to be an efficient OCDMA en/decoder for direct-sequence OCDMA systems [2]. Its advantages include: small size, low insertion loss, simple fabrication technique, and low-cost. Most importantly, it can easily achieve optical phase encoding, which provides far better performance than the amplitude-only encoding [2].

It is desirable to achieve the OCDMA en/decoders with the capacity of dynamic reconfiguration, because this will largely improve the functionality and flexibility of the OCDMA network, and meets the requirements of the internet, which inherently is a burst network. Recently, we proposed such a tunable OCDMA phase en/decoder based on a uniform fiber Bragg grating (FBG) [3].

In this work, we demonstrate a significant improvement from a perspective of speed of the code reconfiguration. Moreover, with a further analysis of the effects of the distributed phase-shift, and their effects on the system performance, we develop a tunable phase en/decoder with a chip rate of 40Gchip/s.

2. Reconfigurable phase encoders

The phase shifts in the SSFBG en/decoders are typically induced by the spatial gap between the gratings forming the individual chips, which are not tunable and discrete. Phase shifts on the grating can also be introduced by applying a variation of the effective refractive index along the fiber, through the post-exposure or thermal techniques. A temperature variation of $\Delta T$ applied on the fiber core of the FBG will induce a variation of $\Delta n_{\text{eff}} \equiv \alpha \Delta T$ on its effective mode index $n_{\text{eff}}$, where $\alpha$ is the thermo-optic coefficient (we neglect the thermal expansion effect because its contribution is only ~10% of the thermo-optic effect) [4]. Assuming the distribution of the effective mode index variation is $\Delta n_{\text{eff}}(x)$ from point $x_1$ in the FBG structure to another point $x_2$, the resultant phase shift will be $\phi = \frac{4\pi}{\lambda_B} \int_{x_1}^{x_2} \Delta n_{\text{eff}}(x) dx$, where $\lambda_B$ is the Bragg wavelength of the FBG.

![Fig. 1 (a) The structure of the 16-chip reconfigurable en/decoder. (b) The distribution of the single phase shift.](image)

Based on this, a tunable phase encoder with multiple phase shifts can be formed from a single uniform FBG. A tungsten wire, with a diameter of 18 $\mu$m, is put in contact with the fiber, and an electrical current passes through the wire. A 16-chip phase en/decoder with a chip length of 2.5mm (corresponding to a chip duration of ~25ps) is thus constructed by positioning 15 parallel wires 2.5mm apart along the FBG, with the first wire being placed 2.5mm into the grating, as shown in Fig. 1(a). The phase-shifts are produced by the heat from the tungsten wires and can be controlled by varying the electrical current along the wires. This causes the temperature variation of the fiber at this point, and consequently results in a tunable phase shift.

For this device, to produce a phase shift of $0.5\pi$, $\pi$, and $1.5\pi$, the electrical currents are respectively 52mA, 70mA and 84mA [5]. The distribution of the effective index variation under these electrical currents can be approximated by the hyperbolic secant square function [5], as shown in Fig. 1(b). The total length of the spatial refractive index distribution for one single phase shift is ~20mm, while the chip length is only 2.5mm, which implies that the phase-shifts are not localized and the chips are coupled together. Below, we will demonstrate that this distributed phase shift will not limit the chip length of the distributed-phase-shift en/decoder.
3. The discrete-phase-shift and distributed-phase-shift en/decoder

As mentioned above, the phase-shifts produced by heating are distributed. Here, by a numerical example, we compare the discrete-phase-shift (fixed-code) and distributed-phase-shift (tunable) en/decoder. Two 15-bit quaternary codes, Q1 and Q2, are chosen from the family $A$ sequences [6]. The discrete-phase encoders are denoted as Q1F and Q2F, while the distributed-phase encoders are Q1T and Q2T. The corresponding decoders are respectively designated by Q1F* and Q2F*, Q1T* and Q2T*. The Bragg wavelength, index modulation, chip length, and total length of all the gratings are respectively 1550 nm, $1.0 \times 10^{-3}$, 2.5 mm and 40 mm. The spatial phases of Q1T and Q1F are shown in Fig. 2(a) and (b). The phase distribution of Q1T is the overlap of multiple phase shifts and each of them follows the distribution shown in Fig. 1(b). We can see that the distributed phase is a good approximation of the discrete one. The pulse responses (when the input pulse width is 2 ps) of the distributed-phase grating Q1T and the discrete-phase grating Q1F are shown in Fig. 2(c) and (d). The response of the grating Q1T is a pulse with distinct edges and a smooth top-section, while that of the grating Q1F is composed of a series of short pulses divided by dips at each phase transition. The temporal phases follow the spatial phases of the corresponding gratings. Shown in Fig. 2(e) is the autocorrelation pulse between the discrete-phase encoder, Q1F, and the distributed-phase decoder, Q1T*, while in Fig. 2(f) the decoder is the grating Q1F* with discrete phase shifts. There are two differences between the autocorrelation Q1F: Q1F* and Q1F: Q1T*. Firstly, the pulse width of Q1F: Q1T* is broader than that of Q1F: Q1F*. Secondly, the side-lobes of the Q1F: Q1T* are higher than that of Q1F: Q1F*. Both of these differences are due to the fact that the phase of the decoder Q1F* and encoder Q1F are completely conjugate, while the phase of the decoder Q1T* and encoder Q1F are only approximately conjugate. Therefore, the pulse width of the autocorrelation is largely dependent on the specific distribution length of the distributed phases. Nevertheless, the length of the phase distribution will not limit the chip length of the distributed-phase-shift en/decoder.

4. Device performances

The experimental setup is as follows. Light from a tunable laser, operated at 1550 nm, is carved through an electro-absorption modulator (driven by a 10 GHz sinusoidal signal), to produce ~20 ps pulses, which are then gated down to 311 MHz using a LiNbO3 intensity modulator. This pulse train is split by a 3 dB coupler into two parts, reflected from the discrete-phase encoders Q1F and Q2F, respectively, and then combined by another 3 dB coupler. A fiber time delay line is utilized to divide the signals from the two encoding gratings in the time domain. Then the combined signal is reflected from the tunable decoding grating. The encoding and decoding gratings used in the experiments have the same designations and parameters as the simulation in Section 3, except that the index modulation is $2.2 \times 10^{-3}$ and, as a result, the peak reflectivity of the gratings is ~50%.

![Fig. 2 The spatial phase of (a) the tunable FBG Q1T, and (b) the SSFBG Q1F (solid line) and Q1T (dashed line). The intensity (solid line) and phase (dashed line) of the pulse responses of (c) Q1T and (d) Q1F. The autocorrelation pulses of (e) Q1F: Q1T*, and (f) Q1F: Q1F*.](image)

![Fig. 3 The power of the decoded pulses (a) when the reconfigurable decoder is switched ON-OFF-ON, (b) when the phase code sequence is switched from Q1T* to Q2T*, and then back to Q1T*.](image)
Firstly, the tuning speed of the reconfigurable decoder is measured by feeding the decoded pulses into an oscilloscope with an effective detection bandwidth of 100MHz. The reconfigurable decoder is switched from ON to OFF, and then back to ON, i.e., from code to no code (uniform grating) and back to code. The power of the reflected signal (in the ON state, the reflected signal is the autocorrelation pulse. In the OFF state, there is only noise) from the reconfigurable decoder is shown in Fig.3 (a). Furthermore, the phase code sequence is switched from $Q1T^*$ to $Q2T^*$, and then back to $Q1T^*$. The power of the reflected signal (including the autocorrelation and crosscorrelation pulses) from the reconfigurable decoder is shown in Fig.3 (b). The response time of all the switching process is observed to be less than 2s. This is due to the fact that the tungsten wire has a fast heat response to the electrical current, and the silica fiber has a fast thermo-optic response.

Then, the decoded pulses are detected with a 20GHz photodiode and fed into a fast sampling oscilloscope. The measured and calculated auto- and cross correlation pulses, when the reconfigurable FBGs are used for decoding, are shown in Fig.4 (a) and (b). For comparison, the results obtained when the decoders are the fixed-code FBGs are shown in Fig.4(c) and (d). The measured ratio between the peak of the cross and auto correlation are respectively ~34% and 30% with the reconfigurable and fixed-code decoders. The autocorrelation pulse widths are measured by the autocorrelator based on the second-harmonic-generation technique. When the decoder is the tunable FBG, the output pulse width is ~39ps, while when the decoder is the fixed-code FBG, it is ~23ps.

The bit error rate (BER) of the autocorrelation pulse is also measured when the data bit rate is 1.25Gb/s. The results are shown in Fig. 4(e). Compared with the back-to-back case, the power penalty is ~0.6dB when the decoder is the fixed-code FBG. An additional ~2.6dB penalty is measured when the decoder is the reconfigurable grating. This additional penalty is mainly due to increased power that exists in the shoulders of the autocorrelation pulses when the distributed-phase grating is used.

5. Conclusions

We have for the first time demonstrated the <2s reconfiguration time of the tunable OCDMA phase en/decoder based on FBGs. Our analysis and experiments also demonstrate that the distribution length of the thermally induced phase-shift does not limit the chip length of the reconfigurable en/decoder. This opens up the possibility of developing practical length, reconfigurable devices of longer code sequences, which will enable more OCDMA users.

References