This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2019.2938021, IEEE Access

Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2017.Doi Number

Transmissive fiber Bragg grating-based delay line interferometer for RZ-OOK to NRZ-OOK format conversion

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This work was supported by National Natural Science Foundation of China (NSFC) (61775074), 111 Project (B07038) and Natural Science Foundation of Guangdong Province, China (2015A030313633).

ABSTRACT We propose a return-to-zero on-off keying (RZ-OOK) to non-return-to-zero (NRZ) OOK conversion scheme based on a transmissive phase-modulated fiber Bragg grating (PM-FBG). The PM-FBG has a spectrum similar to the combination of a delay line interferometer and a narrow band optical filter, which is designed and synthesized using numerical optimization algorithm. The coupling strength of the PM-FBG is almost uniform and the grating period varies along the fiber length according to the optimization method. The designed PM-FBG has been fabricated using advanced ultraviolet laser inscription technique. Experimental results show that such a PM-FBG can perform RZ-OOK to NRZ-OOK format conversion successfully.

INDEX TERMS Bragg gratings, fiber optics, optical fiber devices, optical signal processing, optical fiber communication.

I. INTRODUCTION

All-optical format conversion enhances the flexibility between different formats in future optical networks [1]. Among all data formats, two most common and standard data formats are return-to-zero (RZ) format and non-return-to-zero (NRZ) format. RZ format is not very sensitive to the nonlinear effect and usually used in the high-bit-rate optical time division multiplexing, while NRZ format has a high tolerance to the time jitter and is usually used in the relatively low rate wavelength division multiplexing. Thus, the format conversion between RZ and NRZ formats is an essential and ubiquitous task in future optical network. Hitherto, various all-optical conversion schemes from RZ to NRZ have been proposed and demonstrated. Generally, these schemes can be classified into two categories, namely time domain based solutions and frequency domain based solutions. The time domain based solutions mainly make use of nonlinear devices and effects, including cross phase modulation [2], injected laser diodes [3], injected semiconductor optical amplifier [4], gain clamp effect [5], optoelectronic oscillator [6], highly nonlinear optical fiber [7] and nonlinear optical fiber loop mirror [8]. However, the frequency domain based solutions utilize the linear filtering process, which can be used to suppress sidebands of RZ's frequency spectrum and thus broaden the pulse in time domain. The reported methods include optical fiber delay interferometer (DI) [9, 10], silicon microring resonator [11], fiber Bragg grating (FBG) [12-16].

Compared to other approaches, FBG-based methods offer some advantages such as simplicity, low cost, low insertion loss, polarization independence, and inherent full compatibility with fiber optics systems. However, all the FBG-based methods proposed before make use of FBGs in reflection [12-16], which requires an additional coupler or circulator to assist the conversions.

In this paper, we propose a novel approach based on a transmissive FBG. In this proposal, the use of a coupler or circulator is not required, which can offer the optimum

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energy efficiency and reduce the cost and complexity of the system. In addition, for transmissive FBG, it is more robust against fabrication errors than FBGs in reflection [17]. The transmissive FBG has an almost uniform coupling strength while its period varies along the fiber length, which is the so-called phase-modulated FBG (PM-FBG) [18, 19]. This phase-modulation profile can be directly encoded in a phase mask, which can be potentially developed to a highly reproducible fabrication process.

II. Principle and method

We suppose that $f_{in}(\mathrm{t})$ and $f_{out}(\mathrm{t})$ are the complex envelopes of the input and output of the transmissive PM-FBG respectively, with t as the time variable. Since a transmissive PM-FBG is a linear system, the input and output functions are related by

$$f_{out}(\mathrm{t}) = f_{in}(\mathrm{t}) \otimes h_T(\mathrm{t}) \quad (1)$$

Where $h_T(\mathrm{t})$ is the impulse response of the transmissive PM-FBG, $\otimes$ denotes the convolution operator.

Thus in the frequency domain, these functions can be related by

$$F_{out}(\omega) = F_{in}(\omega)\mathrm{H}_T(\omega) \quad (2)$$

Where $F_{in}(\omega)$ and $F_{out}(\omega)$ are the input and output signals in the spectral domain, $\mathrm{H}_T(\omega)$ is the spectral response of the transmissive PM-FBG and ω is the baseband angular pulsation.

$$\omega = \omega_{opt} - \omega_0 \quad (3)$$

Where ω_{opt} is the optical angular pulsation and ω_0 is the central angular pulsation of the signals.

Theoretically, the function of a DI can be expressed in the time domain as

$$f_{out}(t) = \frac{1}{2}(f_{in}(t) + f_{in}(t-T)) \quad (4)$$

Which means the impulse response is

$$h_T(t) = \frac{1}{2}(\delta(t) + \delta(t-T)) \quad (5)$$

Where $f_{in}(t)$ and $f_{out}(t)$ are the input and output pulse functions, T is the delay time.

Then in the frequency domain, the spectral response can be expressed as

$$\begin{aligned} H_T(w) &= \frac{1}{2}(1+\exp(-iwT)) = \frac{1}{2}e^{-\frac{iwT}{2}}(e^{\frac{iwT}{2}} + e^{-\frac{iwT}{2}}) \\ &= \frac{1}{2}e^{-\frac{iwT}{2}}(2\cos(\frac{iwT}{2})) = e^{-\frac{iwT}{2}}\cos(\frac{iwT}{2}) \end{aligned} \quad (6)$$

Since FBG in transmission is a minimum-phase filter, the amplitude response and phase response are related by means of logarithmic Hilbert transform [20, 21]:

$$\begin{aligned} &\arg(\mathrm{H}_T(\omega) = HT\{\ln|H_T(\omega)|\}, \\ &\ln|H_T(\omega)| = C_0 + HT^{-1}\{\arg(\mathrm{H}_T(\omega))\}. \end{aligned} \quad (7)$$

Where $HT\{\cdot\}$ stands for the Hilbert transform, ln is the natural logarithmic function, and C_0 is an arbitrary real number.

If the desired spectral response (SR) is a minimum phase function, we can get the required amplitude and phase response simultaneously, which is just the case of $H_T(w)$ here.

III. Design results and discussion

Following a numerical optimization process described in [22], we have obtained a grating profile corresponding to the desired spectral function $H_T(w)$, assuming the central wavelength of 1550 nm, with a delay parameter $T = 25ps$. Figure 1 shows the obtained grating strength and grating period. From it, we can see that the coupling coefficient is almost uniform and has a maximum about 300 m^{-1}, while the period varies between -1.8 nm and 1.8 nm. Figure 2 shows the comparison between the ideal spectrum and simulated spectrum. In about 4 nm bandwidth, the simulated spectrum is in a good agreement the ideal spectrum.

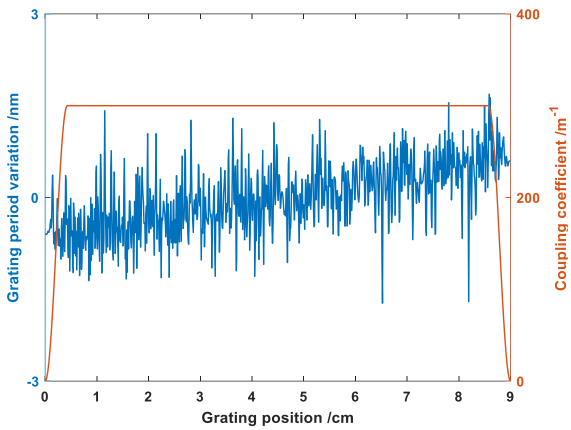

FIGURE 1. **Grating period variation (blue line) and strength (red line) of the designed PM-FBG.**

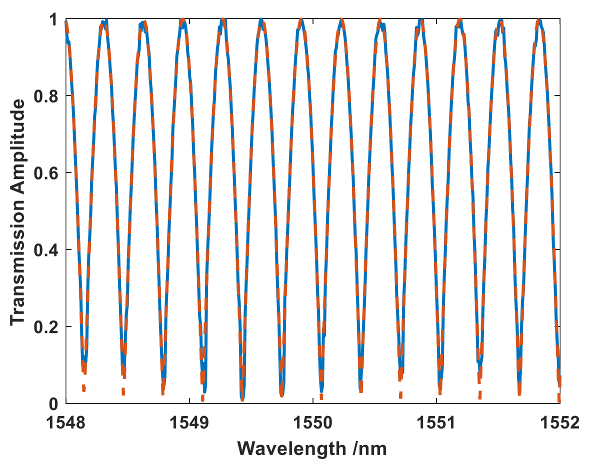

FIGURE 2. **Comparison between ideal spectrum (dashed red line) and simulated spectrum (solid blue line).**

In order to validate the functionality of the designed PM-FBG, a 3 ps FWHM Gaussian pulse centered at 1550 nm is launched to it, obtaining the output signal showed in Fig. 3. We can see that a clear 25 ps delay is realized, which confirms the functionality of the designed PM-FBG.

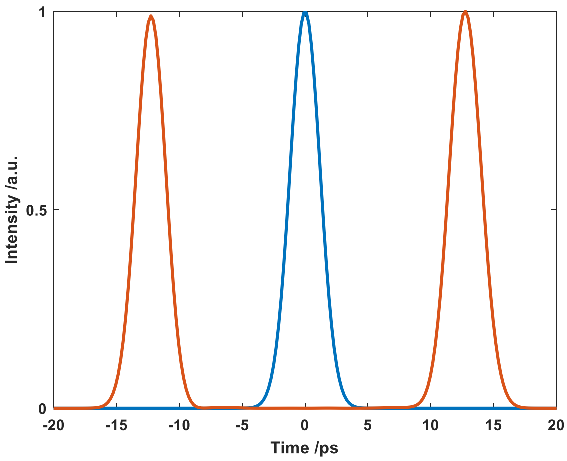

FIGURE 3. The input optical Gaussian pulse (blue line) and the numerically simulated output of the designed PM-FBG (red line).

To evaluate the performance of the PM-FBG based format converter, we simulate its application in a 20-Gbit/s transmission system for RZ-OOK to NRZ-OOK format conversion. We plot the simulated conversion results of the designed PM-FBG and an ideal DI filter for comparison in Fig. 4. The ideal DI filter has a 40-GHz free spectral range (FSR) and its spectrum is the same as the dashed red line shown in Fig. 2. As can be seen in Figs. 4(f) and 4(i), the PM-FBG and the ideal DI based schemes have very similar performance in terms of the eye opening. The Q- factors for the PM-FBG based scheme and the ideal DI based scheme are found to be 9.03 and 9.24, respectively, which are very close and thus confirm the functionality of our proposal.

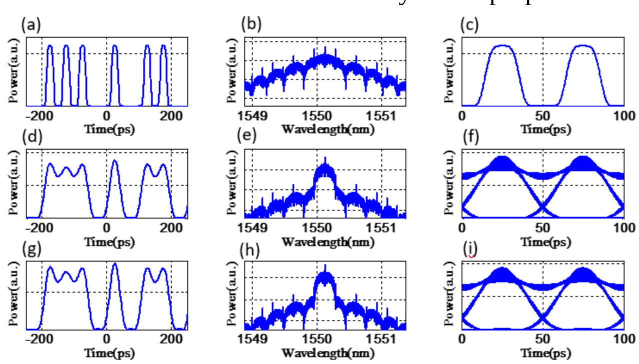

FIGURE 4. Simulated waveforms, power spectra and eye diagrams of (a)-(c) the input RZ-OOK signals, (d)-(f) the corresponding output NRZ-OOK signals by the proposed PM-FBG, and (g)-(i) the corresponding output NRZ-OOK signals by an ideal DI based filter, for 50% duty cycles.

IV. Experimental demonstration

The designed grating structure was fabricated using the ultraviolet laser direct-writing system developed at Aston University, which allows the grating to be created pitch-by-pitch [23, 24]. The coupling strength profile and the varied period were realized by appropriately controlling the ON/OFF of an AO-modulator and moving the phase mask/fibre. The grating structure was made in hydrogen-loaded photosensitive fiber and then stabilized by annealing at 80ºC for 60 hours after the fabrication. Then the fabricated PM-FBG was characterized by using an optical spectrum analyzer, measuring the spectrum from a broadband source transmitted through the PM-FBG. The measured transmission spectrum is shown in Fig. 5, showing a good agreement with the desired response in an approximated bandwidth of 3 nm. The transmission spectrum in Fig. 5 isn't normalized and when we normalize it, the insert loss is about 0.1 dB, which is a relatively low loss compare to FBG in reflection.

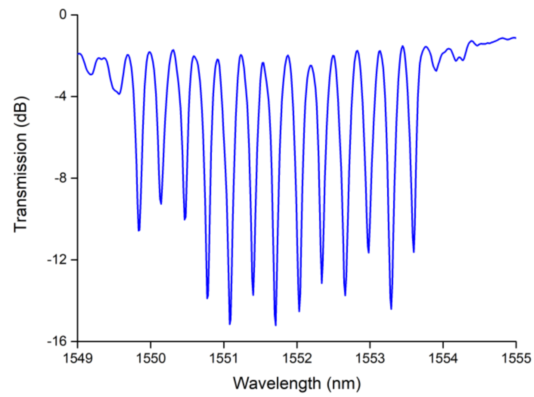

FIGURE 5. Transmission spectrum of the fabricated FBG measured with 0.1nm resolution.

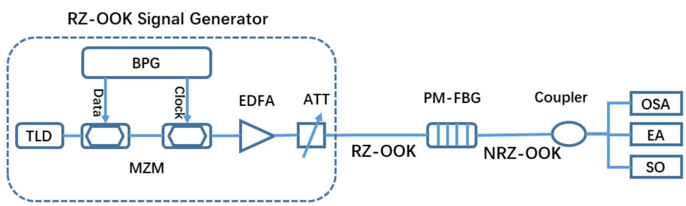

FIGURE 6. Experimental setup for RZ-OOK to NRZ-OOK format conversion.

Figure 6 shows a schematic diagram of the setup for signal pattern observation and bit error rate (BER) measurements from RZ-OOK to NRZ-OOK format conversion. We used a tunable laser diode (TLD), a pulse pattern generator (PPG), and a LiNbO3 Mach-Zehnder modulator (MZM) to generate a 20 Gb/s RZ-OOK pseudo-random binary sequence (PRBS) of length 2^{31}-1. The signal power can be adjusted by the subsequent erbium doped fiber amplifier (EDFA) and an attenuator (ATT). Then the generated RZ-OOK signal was converted by the PM-FBG we designed. Finally, the converted signal was coupled out and analyzed by the optical spectrum analyzer (OSA), the sampling oscilloscope (SO) and the Error analyzer (EA), respectively.

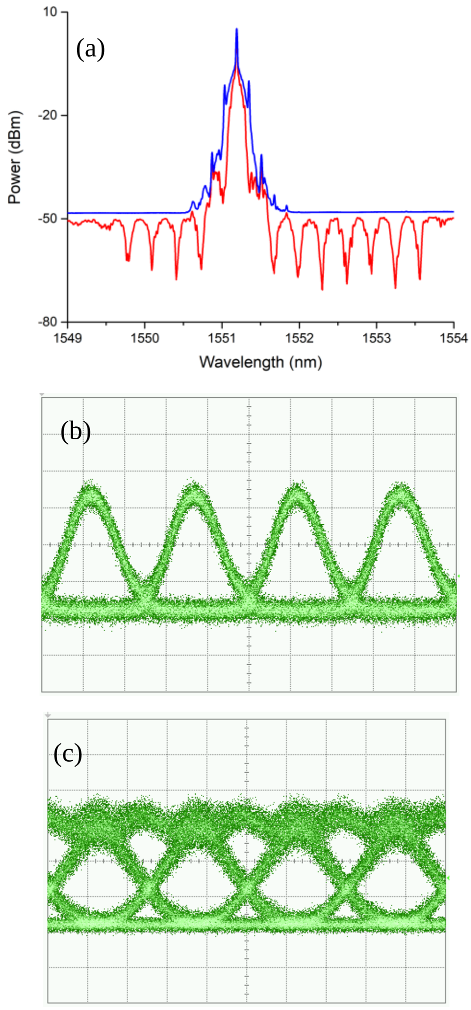

FIGURE 7. (a) Optical spectrum of the generated RZ-OOK signal (blue) and the received signal (red); (b) the eye diagram of the input RZ-OOK signal; (c) the eye diagram of the output NRZ-OOK signal.

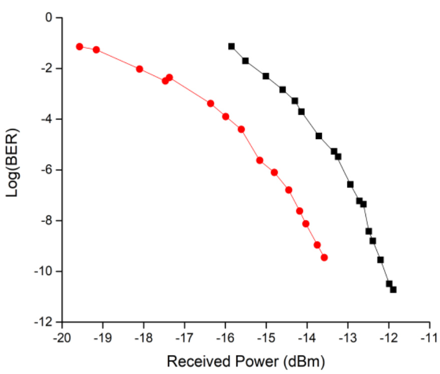

FIGURE 8. BER measurement results. The BER result of the converted NRZ-OOK signal using a commercial MZI (red dot line) and the BER result of the converted NRZ-OOK signal using the PM-FBG we designed (black dot line).

Figure 7 shows the optical spectra and the eye diagrams corresponding to the input RZ-OOK signal and the output NRZ-OOK signal, respectively. Open and clear eyes can be seen and the Q factor of the output NRZ-OOK is about 9 dB. The bit error rate (BER) results of the output signals are also measured and compared with a commercial MZI case, as shown in Fig. 8. The red dot line is the BER result of the converted NRZ-OOK signal using a commercial MZI while the black dot line is the BER result of the converted NRZ-OOK signal using the PM-FBG we designed. From Fig.8, we can see that the receiving sensitivity of the proposed system can achieve -12.39 dBm at BER of 10^{-9}. The plotted curves indicate about 1 dB power penalty. We assume that this power penalty is caused by the phase error of the fabricated PM-FBG. Although we only demonstrate the conversion at the bit rate of 20 Gb/s in this paper, we would point out here that we can process higher rate of RZ-OOK to NRZ-OOK format conversion by designing a similar PM-FBG with a smaller delay parameter.

V. Conclusion

In conclusion, we have numerically and experimentally demonstrated a format conversion from RZ-OOK to NRZ-OOK using a transmissive phase-modulated fiber Bragg grating. Transmissive FBGs are robust against the grating fabrication errors, offer optimum energy efficiency, and can work without an optical circulator or any additional devices to extract the output. The PM-FBG has an almost uniform coupling strength while its period varies along the fiber length. The phase-modulation profile of the grating has been obtained using numerical optimization algorithm and might be possibly encoded in a phase mask, which can make the fabrication process more productively. Experimental results show that the designed PM-FBG has a 1 dB power penalty compared with the commercial MZI, which confirms the efficiency and the validity of the device.

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