Optical temporal encoding/decoding of short pulses using cascaded long-period fiber gratings

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Abstract: A novel, optical temporal encoding/decoding method is proposed and demonstrated. This can be accomplished by passing a short optical pulse through cascaded long-period fiber gratings. It has the advantages of constructing ultrafast codes and developing resistance to interferometric perturbations among the coded pulses. To verify the feasibility as a code generator, two types of codes are generated and compared with the predicted code patterns. In addition, to show an application for an optical code-division-multiplexing system, decoding performances with matched and unmatched decoders are compared.

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References and links

1. Introduction

Many applications such as an optical code-division multiplexing (OCMD) system and an optical packet-switched network frequently require optical temporal encoding/decoding functions [1-3]. Various methods to realize such function have been proposed. In one method, optical fiber delay lines based on multimode fibers [4] or 3-dB fiber couplers [5,6] were used for encoding. The coded signal was received through the decoder having the inverse impulse response to the encoder. In spite of its relatively simple structure, however, it was so bulky that it was difficult to control precisely the time delay among the pulses at high-speed coding applications. To apply a more viable method, several encoding methods based on fiber Bragg gratings (FBGs) have been proposed [7,8], where an incoming short pulse was reflected by a series of FBGs with the same resonant wavelengths placed separately according to the desired code patterns.

In this study, a novel, temporal encoding method that utilizes the mode coupling between the co-propagating modes in cascaded long-period fiber gratings (LPGs) is proposed. This method allows ultrafast coding due to the small difference in the propagating speeds of the co-propagating modes of an optical fiber. This feature also enables precise coding with a relatively wide spatial margin among gratings. Furthermore, a relatively small sensitivity to interferometric perturbations among the coded pulses can be expected since the proposed device is based on fiber gratings. To prove its viability as an encoder and a decoder for the OCDM system application, an encoder was generated, and the coded signal was decoded by two differently coded decoders. The experimental results were compared with theoretical ones.

2. Working principle

An LPG is a device used for mode coupling between the core and the co-propagating cladding modes of an optical fiber. The phase-matching condition of the modes coupled by an LPG is widely known as [9]:

$$\beta_{co} - \beta_{cl} = \frac{2\pi}{\Lambda}$$ (1)

where $\beta_{co}$ and $\beta_{cl}$ are the propagation constants of the core mode and the cladding mode, respectively, and $\Lambda$ is the grating periodicity. In general, the cladding mode has a lower propagation constant than the core mode. Therefore, the optical pulse coupled to the cladding mode by an LPG propagates faster than the uncoupled core mode. By inserting one more LPG in series, the pulse in the cladding mode can be coupled back to the core mode. Hence, two identical, but separated in time, optical pulses can be obtained from a single pulse. The time delay between the pulses is simply calculated as [10]:

$$\Delta T = \frac{L}{c} \Delta m_{eff}$$ (2)

where $L$ is the separation between the LPGs, $c$ is the speed of light in the vacuum, and $\Delta m_{eff}$ is the difference between the effective group indices of the two modes.

Similarly, by cascading a series of LPGs multiple identical optical pulses can be generated from a single short optical pulse. The schematic diagram for constructing a temporal code is shown in Fig. 1. By passing a short pulse through cascaded (n+1)-LPGs, one can have $2^n$ pulses in the core of the fiber. Therefore, by adjusting the separations between the LPGs, code patterns with weights of $2^n$ can be readily obtained. Note that only pulse trains in the core mode are taken after the last grating of the cascaded LPGs. The other $2^n$ pulses in the cladding mode, after passing the last grating, are generally absorbed or scattered at the cladding surface [9]. The inset figures of Fig. 1 are the measured near-field intensity patterns of the fundamental core mode (HE$_{11}$) and the cladding mode (HE$_{14}$) coupled by a single LPG [11].

3. Design and fabrication of cascaded LPGs
LPGs were fabricated by exposing a KrF excimer laser beam on a hydrogen-loaded single-mode fiber through an amplitude mask having a periodicity of 540 µm. Each grating has a length of 20 mm. The fabricated LPGs were annealed at 110 °C to extract the residual hydrogen. To calculate the differential effective group index of the fiber, an LPG pair was fabricated, and its transmission spectrum was measured with a broadband light source.

![Near-field of HE_{14} cladding mode](image)

**Fig. 1.** Schematic diagram of a temporal encoder using cascaded LPGs. Inset figures are the measured near-field patterns of the core mode and the cladding mode.

With the grating separation of 25 cm, the interference fringe spacing was measured to be 2.7 nm; hence Δm_{eff} in Eq. (2) was calculated as 3.56x10^{-3} [9]. To equalize the amplitudes of the coded pulse trains, the strength of each LPG was adjusted to have a 50% coupling ratio. Likewise, all LPG samples were tightly strained to remove the artifacts that might be induced through fiber bending.

For coding, two types of cascaded-LPG configurations were considered. Detailed structures and temporal responses are shown in Fig. 2. The first configuration, as shown in Fig. 2(a), was composed of three identical LPGs cascaded with separations of 20.22 cm and 40.44 cm. Their corresponding time delays were calculated by Eq. (2) to be 2.4 ps and 4.8 ps, respectively. Thus, its resultant code is C_1 (1001010100), where the four 1’s indicate the pulses duplicated by the cascaded LPGs to have the same time intervals of 2.4 ps and the equal intensities. Note that the chip delay time was designed to be 0.8 ps. In the other configuration, the grating separations were chosen to be 33.70 cm and 47.18 cm as shown in Fig. 2(d). The corresponding time delays were 4.0 ps and 5.6 ps with a code of C_2 (1000010100001). Note that C_1 and C_2 were selected to have low cross-correlation.

4. Experiment

A figure-eight fiber laser was used as the input pulse source. It had a 0.6 ps pulse width, a 1.6 MHz repetition rate, and was centered at a wavelength of 1560 nm. Because the response time of the photodetector-sampling oscilloscope combination was too long (~17.6 ps) to detect the actual coded-pulse shape, the temporal responses were measured by a second-harmonic generation (SHG) intensity autocorrelator having a 70-ps scanning range. Hence, when pulse trains having C_1 and C_2 codes are measured by the SHG-autocorrelator, their relative peak distributions are expected as (1002003004003002001) and (1000020200104010020200001), which are shown in Figs. 2(b) and (e), respectively. The corresponding measured code patterns are shown in Figs. 2(c) and (f). The coded pulse trains is thought to be well matched with the theoretical predictions, thereby proving the feasibility of the proposed method for ultrafast coding.

The transmission spectra of both LPG samples were measured with a white light source and compared with theoretical expectations as shown in Fig. 3. Fine interference fringes within the stop band originated from the coupling to the HE_{14} cladding mode of the fiber were
observed. Careful inspection reveals that the interference fringes are composed of several series of peaks in different intervals, which are due to the two different separations between the LPGs.

Fig. 2. The configurations and temporal responses of cascaded LPGs for two codes: \( C_1 \) and \( C_2 \); (a) Structure of cascaded LPGs with \( C_1 \); (b) Predicted response of cascaded LPGs with \( C_1 \); (c) Measured response of cascaded LPGs with \( C_1 \); (d) Structure of cascaded LPGs with \( C_2 \); (e) Predicted response of cascaded LPGs with \( C_2 \); (f) Measured response of cascaded LPGs with \( C_2 \).

Fig. 3. Transmission spectra of two cascaded LPGs with (a) \( C_1 \) and (b) \( C_2 \). Inset figures are the predicted spectra.
As a useful application of the proposed coding method, the basic encoding/decoding functions at the OCDM system are demonstrated. The experimental set-up is shown in Fig. 4. The pulse trains from the figure-eight fiber laser were encoded by the encoder with the code of C1, amplified by an erbium-doped fiber amplifier (EDFA), and sent to two decoders with the codes of C1 and C2. The decoding performance is shown in Fig. 5. Figure 5(a) shows the measured autocorrelator’s output signal when the matched decoder was used, which corresponds to the autocorrelation of C1*C1, where the symbol * is the correlation notation.

The dotted line is the predicted output, and the inset is the estimated pulse train after passing through the decoder. Figure 5(b) shows the case of using the unmatched decoder, which corresponds to the cross-correlation of C1*C2. The contrast of the signal was appreciably degraded compared with the case in Fig. 5(a). Such contrast variation according to the type of the decoders shows good feasibility of cascaded LPGs as the encoding/decoding means for ultrafast OCDM systems. The higher contrast ratio between the matched and the unmatched decoded signals can be obtained by adopting the longer code length.

The encoder is shown in Fig. 4. The first LPGs encode an input short pulse into C1, which is decoded by two cascaded LPGs with C1 (autocorrelation) and C2 (cross-correlation). EDFA is an erbium-doped fiber amplifier.

![Figure 4. Experimental set-up. The first LPGs encode an input short pulse into C1, which is decoded by two cascaded LPGs with C1 (autocorrelation) and C2 (cross-correlation). EDFA is an erbium-doped fiber amplifier.](image)

C1: (1 0 0 1 0 0 1 0 0 1 0 0)  C2: (1 0 0 0 0 1 0 1 0 0 0 0 0 1)

(a)                                                                                       (b)

Fig. 5. Decoded signals obtained with (a) the matched decoder; C1*C1 (b) the unmatched decoder; C1*C2. Dotted line: predicted, solid line: measured. Inset figures are the predicted pulse trains measured after the decoder, but before the autocorrelator.
5. Discussion

The proposed encoder can generate only symmetric code patterns referred to as $2^n$ codes, which restricts the attainable code sets. This is because our encoder is based on a serial coding structure [5]. Nevertheless, the proposed coding method is characterized by several outstanding advantages. Since only one piece of optical fiber is used, the encoder becomes simple and less sensitive to interferometric perturbations compared with the method using fiber-couplers [6]. Also, it does not provide unwanted or troublesome multi-reflected pulses since co-propagating modes are used in the proposed method. The proposed encoder also has a great potential, especially for high chip-rate applications. Due to the small difference in the effective group indices of the co-propagating modes of a fiber, there is a short time delay even with a long grating separation (e.g., 2.4 ps delay with the 20.22 cm grating separation in our experiment). Thus, the spatial margin in the device fabrication process will be improved, which allows us to have high precision in the time delay control. Note that the provided delay, 2.4 ps corresponds the chip rate of ~416 Gchip/s. The maximum chip rate achievable with the 2 cm long LPGs is ~4 Tchips/s because the minimum separation between the gratings can be reduced down to the length of the LPG (2 cm in our case).

Despite these advantages, however, the proposed device has a packaging problem. The cladding mode of a conventional fiber, that we have used, was very sensitive to bending and contacting [12], so that it restricted us to keep the device straight. However, this bending problem can be overcome by utilizing a special fiber that has an inner cladding layer [13,14]. With that inner cladding fiber, the fiber piece between the LPGs can be windable so that the low-chip rate and the long code length can be obtained. We can also think of implementing the device by using planar waveguide device.

When we use a well-designed inner cladding fiber, since the insertion loss of each LPG is small (<0.1 dB) and the coupled inner cladding mode is also a well-guided fiber mode, the total device loss is not big enough to restrict the code length. However, a 3-dB power loss is inevitable because the pulses in the cladding mode after passing the last LPG are not used. For an example, in principle, the total loss of cascaded 11 LPGs, which generate $1024 (2^{10})$ chip pulses, does not exceeds 5 dB even including the fiber propagation loss.

In our experiment, LPGs had broad coupling bandwidths of >20 nm; on one hand, this ensures accommodating the broader range of the input wavelength, on the other hand, probably it restrics providing hybrid two-dimensional wavelength-time codes [15]. LPGs in our encoder were fixed, not tunable. However, we can tune or switch the LPGs by varying temperature or strain on the gratings [14] or by using hybrid parallel-serial configurations [5]. It has been reported that a wide band LPG spectrum could be turned on and off by varying temperature. Where the specially designed dispersion characteristic of the inner-cladding mode was utilized.

6. Conclusions

This study has proposed a novel ultrafast coding method based on cascaded LPGs. The proposed device was composed of a series of LPGs that were fabricated with the same conditions (i.e., grating periodicity, coupling strength, etc.). The strength of each LPG was kept to have a 50 % coupling ratio, which enabled equal intensity distribution among the coded pulses. The separations between the LPGs were adjusted to produce different coding patterns. The pulse trains coded with the proposed encoder were shown to vary with the change in the LPG separations. To demonstrate optical CDMA application, the matched/unmatched decoding performances were compared. One encoder and two decoders, of which one was matched and the other one was unmatched with the encoder, were fabricated. When the matched decoder was used, the decoded pulse trains measured with an SHG-autocorrelator had high contrast. On the other hand, the unmatched decoder gave poor contrast. The proposed device ensures precise time delay control. It also shows its powerful potential in ultrafast coding for the OCDM system and optical signal processing applications.
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