Optical pulse multiplication and temporal coding using true time delay achieved by long-period fiber gratings in dispersion compensating fiber

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Abstract: We present an optical pulse multiplication and temporal coding method for OCDMA systems. The true time delay among the pulses was obtained by utilizing the difference in the propagation speeds of the core mode and a co-propagating cladding mode coupled by a long-period fiber grating. By cascading gratings we could get an equally spaced 40-GHz pulse train from a 10-GHz input train. The dispersion compensating fiber having an inner cladding structure enabled us to have the gratings that were not sensitive to the polymer jacket on the cladding surface, and also allowed shortening the device length. Various coding and decoding of a pulse train are possible by controlling the separations among the gratings.

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1. Introduction

Fiber gratings, which can be broadly classified as fiber Bragg gratings (FBGs) and long-period fiber gratings (LPGs) based on their periods compared to the operating wavelengths, have been extensively investigated due to their simplicity in fabrication, good wavelength selectivity, high flexibility, low back reflection and so on [1][2]. Their use has been extended to the time-domain applications such as the multiplication of an optical pulse train [3][4] and the optical temporal encoding/decoding implemented by using an array of FBGs and superstructured fiber gratings [5][6]. Recently, we have reported the use of cascaded LPGs written in a single mode fiber (SMF) to get a high repetition-rate pulse train [7] and to realize a high-speed optical encoder/decoder for an optical code division multiple access (OCDMA) system [8]. Where the true time delay (TTD) induced by the difference in the propagation speeds of the core mode and a co-propagating cladding mode of an SMF was utilized. However, the cladding modes of the SMF were affected by the surface condition of the cladding layer and the differential effective group index (DEGI) between the core and the cladding modes was relatively small. These problems have caused the significant limitations in getting real applications.

In this work, we report the use of cascaded LPGs in a dispersion compensating fiber (DCF) to have a more realistic implementation of a multiplication of the repetition rate of an optical pulse train and a temporal coding/decoding method for the OCDMA system. The DCF used for this work had an inner cladding structure, which supported an inner cladding mode. By using the inner cladding mode coupled by an LPG, we could overcome the cladding surface sensitivity of the fiber gratings. In addition, we could get a relatively higher DEGI, so that a larger TTD could be obtained with a shorter device length. Based on this scheme, we have successfully obtained a 40-GHz pulse train from a 10-GHz one and implemented an OCDMA system operating.

2. Principle of true time delay

An LPG is a device used for mode coupling between the core and the co-propagating cladding modes of an optical fiber. 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 using another 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 but within a single piece of fiber. The time delay, $\Delta T$, between the pulses is simply calculated as [7]:

$$\Delta T = \frac{L}{c} \Delta m_{\text{eff}}$$

where $L$ is the separation between the LPGs, $c$ is the speed of light in vacuum, and $\Delta m_{\text{eff}}$ is the DEGI of the two modes. Thus, by cascading a series of LPGs multiple identical optical pulses can be generated from a single short optical pulse. The schematic diagram for the realization of a true time delay is illustrated in Fig. 1. The inset figures show the measured near-field intensity patterns of the fundamental core mode and a cladding mode of a DCF [9]. If we use $N$ LPGs in series, we can have $2^{N-1}$ pulses from a single pulse. The separations among the pulses are determined by the separations of the LPGs. Therefore, $N$ cascaded LPGs will constitute $N-1$ delay elements and multiplicate $2^{N-1}$ optical pulses. Each delay element consists of two identical but separated LPGs. Note that only pulse trains in the core mode are
taken after the last grating of the cascaded LPG’s. The other $2^n$ pulses in the cladding mode, after passing the last grating, are generally absorbed or scattered at the cladding surface [13].

Fig. 1. The schematic diagram of realization of a true time delay with a cladding mode by using cascaded LPGs. Inset figures are the measured near-field patterns of the core mode and a cladding mode of a DCF.

3. Inner cladding fiber

The spectral property of an LPG is sensitive to the condition of the cladding surface due to the evanescent field reaching out of the cladding surface. This sensitivity adversely limits the use of LPGs in telecommunication applications. A DCF has an inner cladding layer between the core and the outer cladding. The so-called inner cladding modes also called as higher order modes (HOM) are confined to the inner cladding layer [9] which is far away from the outer cladding of the fiber. Further, due to the dispersive property of the HOM in a DCF [9], the DEGI of the inner cladding mode is larger than that of a conventional SMF. Therefore, by writing LPGs in the DCF, which enables coupling between the core mode and the inner cladding mode, we can realize practical optical pulse multiplication and optical temporal coding/decoding.

Fig. 2. The refractive index profile of the DCF used for the experiment. It had an inner cladding layer.

The refractive index profile of the DCF used for the experiment is shown in Fig. 2. It was similar to that of a double cladding fiber or a few-mode fiber [10]. The center core had a diameter of about 3.1 μm with a refractive index 2.5 % higher than that of the outer cladding layer. It had one reduced (-0.5 %) ring and one raised (+0.5 %) ring layers concentric to the core. The inner cladding structure is believed to support a mode or modes having the effective index between the raised ring layer and the outer cladding layer.
To verify the formation of the inner cladding mode in the DCF, the near-field image of the suspected inner cladding mode was taken with a tunable laser and an IR CCD camera. The right inset figure of Fig. 1 is the measured modal intensity profile of the suspected mode. The same image is redrawn in Fig. 3(a) for easier comparison with the simulated one of Fig. 3(b). As can be seen, both figures are similar with each other in the sense that it has a single peak at the center region and a single ring-shape peak near the inner cladding region. We can also see that the modal intensity near the surface of the cladding (having a diameter of 125 μm) is negligible. The rather strong field in the right side of Fig. 3(a) is believed to originate from imaging taking apparatus.

![Image](https://via.placeholder.com/150)

**Fig. 3.** (a) The measured near-field image of the inner cladding mode coupled by a single LPG fabricated in the DCF and (b) the simulation result of the modal field distribution of the inner cladding mode.

As a second verification of existence of the inner cladding mode, an LPG pair (LPGP) was fabricated in the DCF. Each grating was designed to have a 700 μm periodicity and 20 mm length. The separation between the LPGs was 250 mm and the original acrylate coating or jacket on the fiber was not removed except the grating regions for the UV exposure. Figure 4 shows the measured transmission spectrum of the LPGP. It has three resonant peaks. As well known each peak is resulted from the mode coupling from the fundamental core mode to the corresponding cladding mode of the fiber. In the figure, we can see the first resonant peak near 1510 nm has dense interference fringes; the fringe is too dense to be distinguished individually. The second peak in the middle also has interference fringes, but the fringe contrast is not good. The last one near 1600 nm has no interference fringes.

![Image](https://via.placeholder.com/150)

The formation of the interference fringes in an LPG pair has been extensively studied [2][12]. The fringes were resulted by the interferences between the core mode that has not been coupled by both LPGs and the one that was coupled to the cladding mode by the first LPG and then re-coupled to the core mode by the second LPG [13][14]. The spacing of the interference fringes is determined by the DEGI of the fiber and the separation between the LPGs [13].

Therefore, the non-existence of the interference pattern in the third peak of Fig. 4 represents that the corresponding cladding mode disappeared before being coupled again to the core mode of the fiber. The polymer-jacket between the LPGs absorbed or scattered out the cladding mode that had been coupled by the first LPG. With the same token we can say that the high contrast interference fringes in the first peak represent that the corresponding cladding mode was not affected by the polymer-jacket on the cladding surface. The similar experiments have been done with a series of index matching oils instead of the polymer-jacket. After removing the jacket completely, we have applied the index matching oils one by one but no change in the interference fringes was observed. From these series of observations,
we can say that the resonant peak appeared near the 1510 nm wavelength of Fig. 4 originated from the coupling to the inner cladding mode of the DCF having the index profile of Fig. 2.

Fig. 4. The transmission spectrum of the LPGP made in the DCF. The poly-acrylate coating between two gratings was not removed. The first peak, left most, has good contrast interference fringes, but the third peak, right most, has no interference fringes. The middle one is between.

As was mentioned, since the spacing of the interference fringes was related to the DEGI of the fiber, from the interference fringes in the first mode of the DCF, the differential effective index and the DEGI were calculated as shown in Fig. 5. The DEGI of the DCF was $12.71 \times 10^{-3}$ at 1510 nm, which was about 3.5 times larger than that of a conventional SMF ($3.56 \times 10^{-3}$) [7][8].

The environment-insensitive inner cladding mode enabled us to have easier handling of the fiber and the larger DEGI made the device length short enough to be implemented in a laboratory. However, the confinement of the inner cladding mode of the DCF was too weak to keep the mode even in a winded fiber. Therefore, for experiment, the fiber embedding a series of cascaded LPGs was kept straight. This bending sensitivity of the inner cladding mode of the DCF limited the number of cascadable elements and the operating frequency of the system.

Fig. 5. The differential effective group index (left) and the differential effective index (right) calculated from the interference fringes in the first resonant peak of Fig. 3.
4. Experiment and results

4.1 Optical pulse rate multiplication

The strengths of all gratings were designed to have 3-dB coupling ratio and the acrylate coating on the fiber was removed only at the UV exposing regions, which was possible because of utilizing the inner cladding mode of the DCF. Hydrogen loading was done under 100 atm and 100 °C for four days. The period of the amplitude mask used for making the LPGs was 780 µm, which located the resonant wavelength of the first inner cladding mode to a wavelength of 1554 nm. The length of each LPG was 10 mm, which was shortened by half from the one used for getting Fig. 4. This gave a rather wide resonant peak of a 8.3 nm bandwidth at a 2.5 dB coupling ratio. The wider bandwidth could increase the tolerance in fabricating identical several LPGs. Additionally, a test LPGP having a separation of 341.0 mm was fabricated to calculate the DEGI of the DCF at the wavelength of an input source beam, which gave us 11.00×10⁻³ as the DEGI of the fiber at a 1554 nm wavelength.

The experimental setup for the demonstration of the pulse multiplication with the DCF was illustrated in Fig. 6. By virtue of the large DEGI, we could use an actively mode locked fiber ring laser as the initial optical trains, which had a pulse width of 1.5 ps, repetition rate of 10-GHz, and could adjust the operating wavelength from 1545 nm to 1560 nm. The temporal responses of the proposed devices could be measured with a 45-GHz photodetector and a sampling scope.

Two sets of LPGPs were prepared and cascaded in series as in Fig. 6. The first LPGP, LPGP-1, had a separation of 1363.9 mm, and the other one, LPGP-2 had a half of it 682.0 mm. From eq. (1) and the DGEI obtained with the test LPGP, the obtainable time delays were calculated to be 50 ps with the LPGP-1 and 25 ps with the LPGP-2 as shown in the figure. Since the pulses duplicated by the LPGP-1 would be duplicated by the LPGP-2 four times pulse multiplication was expected. In other words, a 40-GHz pulse train was expected from the original 10-GHz pulse train.

![Fig. 6. The experimental setup for optical pulse multiplication by using the cascaded LPGs made in DCF. An active mode lock fiber laser was used as an initial optical pulse train. AMFRL, actively mode locked fiber ring laser. PC, polarization controller. PD, 45-GHz photodetector.](image)

Figure 7 shows the result pulse trains of the experiments done for three considered cases; 50 ps time delay (two times multiplication), 25 ps time delay, and four times pulse multiplication. Each figure shows the average optical power measured by the photo-diode of Fig. 6. Figure 7(a) shows the initial pulse train. We can see that the pulses were separated by 100 ps, corresponding to a 10-GHz train. Fig. 7(b) is the pulse train measured after passing the LPGP-1. We can see that the pulse train separated by 50 ps, corresponding 20-GHz, was obtained.
Figure 7(c) is the temporal response of the LPGP-2 that was designed to give 25 ps time delay. We can see that from the pulse train of Fig. 7(a) we obtained another similar pulse train but shifted by 25 ps in time. To get the Fig. 7(c), the LPGP-1 was removed from the scheme of Fig. 6. Finally, by cascading the two LPGPs we got the pulse train of Fig. 7(d). The pulses were equally separated by 25 ps, which corresponded to a 40-GHz pulse train. These measurements enable us to say that we could clearly implement the 4 times pulse train multiplication by using cascaded LPGs; from a 10-GHz train to a 40-GHz one. The small inequality in the height of the pulses of Fig. 7(d) is originated from the fabrication error in the strengths of LPGs. The desing strengths were 3 dB for all LPGs. In our experiments, due to the lack of enough bandwidth of the photo-detector (45-GHz) and the sampling scope (50-GHz), the temporal responses in Fig. 9 show a pulse–width broadening. As increasing repetition ratio, the pulses of Fig. 9(d) overlapped each other.

![Fig. 7. The temporal responses of the proposed device: (a) Initial pulse train with a 10-GHz repetition rate, (b) Two times multiplied pulse train obtained by LPGP-1. It has a 50 ps repetition period, (c) 25 ps time delayed pulse train obtained with LPGP-2 only, (d) Four times multiplied pulse train obtained by using both LPGPs. It has a 25 ps repetition period or 40-GHz repetition rate.](image)

### 4.2 Temporal encoder/decoder for OCDMA

The experimental setup to verify the feasibility of our coding/decoding scheme is shown in Fig. 8. Two orthogonally coded signals were generated and decoded by the LPG devices proposed and demonstrated in the previous section of this article. The same active mode locked fiber laser having a pulse width of 1.5 ps and repetition rate of 10-GHz was used as the initial input optical source. Note that the chip spacing, $\tau$, was designed to have 4.16 ps for the generated code sets.
The two encoders were designed to give mutually orthogonal codes by adjusting the separations among the gratings, and the decoder was designed to be the same as one of the encoder, encoder-1 in the figure. The encoder-1 was composed of three identical LPGs cascaded with separations of 340.1 mm and 682.0 mm, which corresponded to time delays of 12.48 ps and 24.96 ps, respectively. Thus, its resultant code was expected to give \( C_1 \) (100100100100). On the other hand, encoder-2 was designed to give code \( C_2 \) (1000010100001). The grating separations were 568.3 mm and 795.6 mm and their corresponding time delays were 20.80 ps and 29.12 ps, respectively. However, the proposed coding scheme cannot provide arbitrary codes because of its symmetric structure. It can give the so-called “2n” code, and the number of attainable codes is restricted [15].

Figure 9 shows the code patterns produced by the encoders and measured by the sampling scope of Fig. 8. We can see that both code patterns are well matched with the expected ones. In detail, in the left of Fig. 9(a), we can see 4 peaks barely distinguished each other. Each peak corresponds to the code digit “1” of the code pattern of \( C_1 \) (100100100100). Between adjacent peaks two code digit “0” are located. In the same way, the peaks of Fig. 9(b) correspond to the code digit “1” of the code pattern \( C_2 \) (1000010100001). There are four 1’s in the code but the figure show only three. Two 1’s in the middle of the code are merged together and appears as a single rather big peak. In other words, the system apparatus was not fast enough to accommodate the chip spacing of \( \tau = 4.16 \) ps, corresponding to a 240-GHz maximum coded pulse rate. The slope in the peak powers of the encoder-1, Fig. 9(a), is caused by the non-uniformity in the grating coupling ratio. To fabricate LPGs, the fiber was hydrogen loaded and then annealed after inscribing the gratings by UV. During annealing process, however, the LPG has unwanted resonant wavelength shift in general. Since it is not easy to predict the exact amount of annealing-affected wavelength shift, the grating strength at the operating wavelength could be slightly different from the designed one. This problem can be overcome by utilizing a high-photosensitivity fiber, which does not need the troublesome hydrogen loading and annealing processes.
Fig. 9. The temporal responses of the encoded signals with (a) the code of C1 \((100100100100)\) and (b) the code of C2 \((1000010100001)\).

The decoding performance of the OCDMA scheme of Fig. 8 was measured and shown with Fig. 10. Actually three measurements were done with the 2 encoders and 1 decoder. At first, Fig. 10(a) was obtained with only the encoder 1, of course with the decoder, while discarding the encoder 2 from the configuration. It was the matched decoding case, thus, expected to give autocorrelation of \(C_1^*C_1\). The figure shows a well-distinguished 10-GHz pulse train. The second measurement was done with the encoder 2 while discarding the encoder 1. As Fig. 10(b) shows, the detected signal had no appreciably noticeable pulses. It was the case of unmatched decoding case giving the crosscorrelation of \(C_1^*C_2\). Finally, both encoders were installed simultaneously in the configuration and only one decoder was used. It was the case of mixed correlation of \((C_1+C_2)^*C_1\). As can be seen with Fig. 10(c), we could retrieve the original 10-GHz pulse train without being appreciably affected by the presence of the encoder 2. These measurements are believed to give good feasibility of the cascaded LPGs as the encoding/decoding means for the OCDMA system. For getting a longer code length and/or having a better contrast in the output pulse train, more number of LPGs are asked to be cascaded.

Fig. 10. Decoded signals of the pulse train encoded by (a) only the matched encoder; \(C_1^*C_1\), (b) only the unmatched encoder; \(C_1^*C_2\), and (c) both encoders; \((C_1+C_2)^*C_1\).

4. Discussion

In our experiment, we have implemented only four times pulse multiplications and two encoders were utilized. The number of LPG elements was three for each encoder and decoders. These were barely enough just to show the feasibility of the LPG-based devices in OCDMA. For getting a practical device, a longer code length and/or a better contrast in the output pulse train are required, which asks using more number of LPGs. However, increasing the number of LPGs will give lots of engineering problems. Further, stability of the system to bending, temperature, and polarization will be asked also.

One of the advantages of an LPG-based device is its long length. As measured and shown with Fig. 6, 1.364 meter-long DCF gave 50 ps delay. Since the time delay is linearly...
proportionally to the fiber length. An error of 0.1 ps in time can be caused by an error of 2.7 mm in fiber length. Even though there might be stitching error in achieving a long LPG separation, we can keep the stitching error smaller than 1 mm. Therefore, the positioning error in implementing a practical system might be small enough not to give a severe problem in the system performance.

However inversely, due to its long length, there might be problems in packaging, bending, and mechanical deformation. With the DCF fiber, the cladding mode could not propagate with a bending radius smaller than 30 cm. It is not long enough for winding the fiber, which is asked to pack many cascaded LPGs. Even though the DCF was not good enough for practical applications, these problems can be or at least be reduced by introducing a specialty fiber. A specialty fiber called few mode fiber was reported [10], which could be windable even carrying cladding mode. However, the fiber was not available for us at the moment of experiment. We are designing the fiber for our future experiment.

The proposed system has temperature sensitivity because the differential effective index of the optical fiber would be changed with temperature variation. Due to the long device length, the temperature sensitivity of the whole system could not be measured. However, the sensitivity of the LPG in DCF fiber was measured. As increasing temperature, the resonant wavelength of the LPG increased with a linear slope of $\Delta \lambda / \Delta T \equiv 0.077 \text{ nm/}^\circ C$. Further more, the DEGI (differential effective group index) was varied by $1.97 \times 10^{-9} / ^\circ C$. Therefore, for the fiber length of 1.364 m giving 50 ps time delay, the temperature-affected time delay variation is estimated by 8.96 fs/$^\circ C$, which is low enough for indoor application.

Figure 10 shows that the power ratio between the main and the shoulder powers is ~ 6.5. The appearance of the pedestal in Fig. 10 originates from the incoherent and the coherent correlation between the pulses. Therefore, the power ratio remains between 4 and 16 in theory. The power ratio is also affected by the phase statue of the pulse having a different optical path and the state of polarization. Even though we are doing analysis by using a system simulator to get more complete understanding, due to the limited bandwidth of the apparatus, the analysis is limited. Implementing a system operating within the bandwidth of the apparatus, instead of increasing the system bandwidth, will be useful to isolate the problem of pedestal. However, the lower system bandwidth asks the longer device length that can not be covered with the DCF fiber as discussed previously. Therefore, developing dedicated specialty fiber should be preceded to implement a practical system.

During the experiments, we have observed that the system was sensitive to polarization. For the LPG in its ideal condition, there is no polarization sensitivity. However, depending on the grating fabrication method, PDL and PMD can be invoked. In our previous work, we have observed that the UV illuminating method could give PDL on the LPG [16]. However, the PDL problem of LPG can be reduced by illuminating the UV beam symmetrically [17].

The system implemented with DCF is not good enough to be practically used. It has many limitations. However, it showed, we believe, good feasibility of the LPG-based OCDMA system. Provided a specially designed fiber will be available, it will be possible to get a practical and reliable OCDMA system.

5. Conclusions

We have reported the use of cascaded LPGs made in the dispersion compensating fiber having an inner cladding structure as the optical pulse multiplication and the encoding/decoding devices for high-speed OCDMA systems. We also have investigated the properties and the benefits of the high differential effective group index ($11.0 \times 10^{-3}$ at 1554 nm) of the fiber, which enabled reducing the devices length. The true time delay could be obtained within a single piece of fiber by using the fast propagating speed of the inner cladding mode coupled by the cascaded LPGs. The experiment showed that a 40-GHz repletion rate pulse train could be obtained from a 10-GHz pulse train by cascading 3 LPGs or by using two LPG pairs. By adjusting the spacing between the LPGs, various temporally coded patterns could be generated. The optical encoder/decoder having a 4.16 ps chip spacing operating at a 10 GHz has been successfully demonstrated. Based on this scheme, we have implemented an OCDMA
system composed of 2 encoders and 1 decoder. The decoder could retrieve the original 10-
GHz pulse train from the signal generated by the two orthogonal encoders. The LPGs were
not sensitive with the polymer jacket on the fiber surface, which was possible by utilizing the
inner cladding mode of the fiber. The proposed device is expected finding its application in
manipulating the temporal characteristics of the pulses used for future high-speed, high-
capacity optical communication systems and photonic systems.

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