

High Repetition Rate Optical Pulse Multiplication with Cascaded Long-period Fiber Gratings

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We propose and demonstrate a novel optical pulse multiplier applicable to OTDM (Optical Time Division Multiplexing) systems using cascaded long-period fiber gratings. We have exploited the fact that each mode in a fiber has a different propagation constant to obtain time delays among optical pulses. The proposed scheme could realize high-frequency optical pulse multiplication for optical short pulse trains. We have successfully implemented two, four, and eight times multiplications with the maximum repetition rate of 416.7 GHz. The obtained pulse delays are well matched with the simulated ones.

OCIS codes : 060.2310, 050.2770, 060.2330, 060.2340, 060.7140

I. INTRODUCTION

Optical time division multiplexing (OTDM) systems require optical sources that are capable of generating highly synchronized trains of short pulses at ultrahigh repetition rates. Recently, a single mode optical fiber [1] and a nonzero dispersion-shifted fiber [2] were used as dispersive media to get repetition-rate multiplications. The use of sampled fiber Bragg gratings [3] and chirped fiber gratings [4,5] as the dispersive elements was proposed. An integrated-optic multiplexer based on a hybrid planar light-wave circuit [6] was also reported. In this work, we propose a novel technique suitable for ultra-short pulse multiplication based on long period fiber gratings (LPGs). The proposed method has great tolerance to fabrication errors, which promises high precision in applications [3-5]. It also has a finite impulse response without the noise caused by multiple reflections such as in the fiber Bragg grating cases [7]. We demonstrate the multipliers that give two, four, and eight times multiplications with the maximum repetition rate of 416.7 GHz (pulse separation of 2.4 ps). The measured performance of the proposed system is discussed and compared with the simulation results.

The feasibility of pulse multiplication using LPGs has been reported [8]. At that time only a pair of LPGs was used and a single tiny duplicated pulse was observed. The basic scheme of the duplication was based on the effective index difference between the core and the co-propagating cladding modes of an optical fiber. An

LPG divides an input pulse into the core and the cladding modes. Since the effective index of the cladding mode is smaller than that of the core mode, the pulse in the cladding mode travels faster than the one in the core mode and hence the two pulses are separated in time. The duplicated pulse in the cladding can be coupled back to the core of the fiber by cascading the second LPG in series. By selecting an appropriate cladding mode and choosing proper separation between the LPGs, we could obtain the required time delay between the two pulses. For the pulse duplication we needed only two LPGs but for multiple duplication or multiplication, we need to cascade multiple LPGs with appropriate separations among them.

II. PRINCIPLE OF PULSE MULTIPLICATION BASED ON LPGs

The configuration of the proposed pulse multiplier is shown in Fig. 1 (a). It is composed of $N-1$ delay elements. The i -th delay element consists of two identical LPGs separated by a distance L_i . Therefore, the total number of LPGs is N . An incident optical pulse is separated by the first LPG into the core and the cladding modes, which pass through the length L_1 and then are re-coupled by the second LPG. Thus, after passing the first delay element there exist four duplicated pulses, two in the core and the other two in the

cladding. The third grating, which is a part of the second delay element, divides the pulses in both the core and the cladding, thus produces eight pulses. When the separation length L_2 is a half of L_1 , after passing the third LPG, we will have four equally spaced pulses in the core of the fiber. In the same way, when the grating separation of the successive delay element is the half of the previous one, we will have 2^{N-1} pulses in the core and the other 2^{N-1} pulses in the cladding of the fiber. After passing through the last LPG, the pulses in the cladding mode are not re-coupled into the core mode but absorbed or scattered at the coating on the cladding surface of the fiber [9]. The near field images of the field profiles before and after passing through the first LPG are shown in Fig. 1 (b) and (c), respectively. Figure 1 (b) is the typical core mode pattern, while Fig. 1 (c) is the mixture of the core mode and the HE_{14} cladding mode, which extends up to the cladding surface.

The repetition period T_p , or the time delay between the adjacent pulses after passing the p -th delay element, is given as [8]

$$T_p = \frac{L_p}{c} \Delta m_{eff} \quad (1)$$

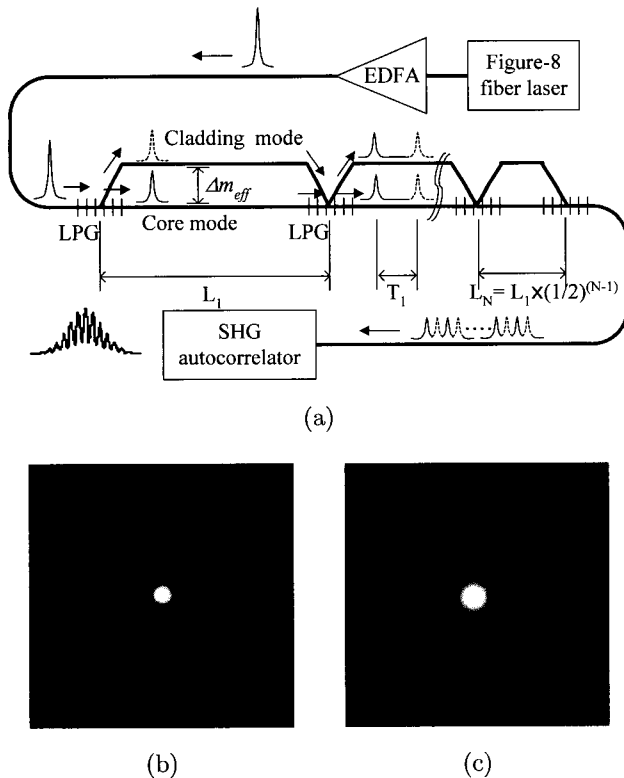


FIG. 1. (a) Schematic of optical pulse multiplication using cascaded LPGs. (b) Near field images of the core mode and (c) the HE_{14} cladding mode measured at 1560 nm wavelength.

with,
$$\Delta m_{eff} = \Delta n_{eff} - \lambda \frac{d}{d\lambda} \Delta n_{eff} \quad (2)$$

and
$$L_p = L_1 \left(\frac{1}{2}\right)^{p-1} \quad (3)$$

where, L_1 is the grating separation length of the first delay element, and Δm_{eff} is the difference between the effective group indices of the core and the cladding modes of the fiber [10].

III. RESULTS AND DISCUSSION

The LPGs for this work were fabricated by illuminating a KrF Excimer laser on Samsung's conventional single-mode fiber having the numerical aperture of 0.11

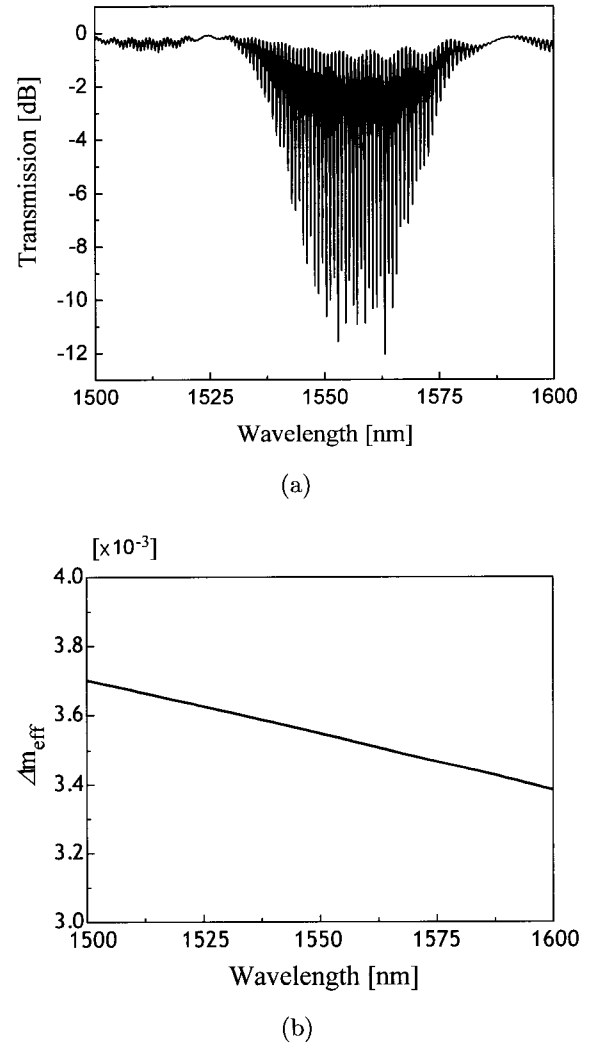


FIG. 2. (a) Transmission spectrum of a pair of LPGs separated by 808.68 mm and (b) the differential effective group index calculated from the fringe pattern of Fig. 2 (a).

and the cut-off wavelength of $1.23 \mu\text{m}$. Hydrogen loading was done at 100 atm for three days. The period and the length of the gratings were fixed at $540 \mu\text{m}$ and 20 mm , respectively, which located the resonance wavelength of the LPG close to the center wavelength of the input source and gave a 3 dB coupling ratio. A translation stage having a $0.1 \mu\text{m}$ resolution was used to get high precision in the separations among the LPGs. Figure 2 (a) shows the transmission spectrum of the delay element that was composed of two LPGs separated by 808.68 mm . The spectrum was composed of many fine interference fringes. From the spacing of the fringes, the differential effective group index of the fiber was obtained as a function of wavelength [10] and shown in Fig. 2 (b). The fringe spacing at the wavelength 1560 nm was measured to be 0.855 nm , which gave $\Delta m_{\text{eff}} = 3.52 \times 10^{-3}$. Since the separation length L_1 is 808.68 mm , from Eq. (1), the time delay T_1 is calculated to be 9.6 ps .

As the input pulse source, a self-starting mode-locked figure-eight fiber laser was used, which had a 0.6 ps full width half maximum (FWHM), a 1.6 MHz repetition rate, and was centered at 1560 nm [11]. An erbium-doped fiber amplifier was used to adjust the power

level of the input pulses. An optical spectrum analyzer and a second-harmonic generation (SHG) autocorrelator were used for measuring the spectral and the temporal responses of the proposed multiplier.

Figure 3 (a), (b), and (c) show the measured and the simulated autocorrelation traces of the output pulse trains for $2\times$, $4\times$, and $8\times$ pulse multiplications, respectively. The two times multiplication generated by a single delay-element ($L_1 = 808.68 \text{ mm}$) provided a repetition period T_1 of 9.6 ps as shown in Fig. 3 (a). The intensity ratio between the central and the side peaks was approximately 2:1 in the autocorrelation trace, which means that the intensities of the duplicated pulses were similar to each other. We note that all LPGs were designed to have the same 3 dB coupling strengths. The inset figure shows the estimated actual pulses. With two delay elements ($L_1 = 808.68 \text{ mm}$, $L_2 = 404.34 \text{ mm}$), we have obtained 4-times multiplication with $T_2 = 4.8 \text{ ps}$ as expected. Finally, with three delay elements ($L_1 = 808.68 \text{ mm}$, $L_2 = 404.34 \text{ mm}$, and $L_3 = 202.17 \text{ mm}$), the 8-times multiplication was obtained with $T_3 = 2.4 \text{ ps}$ which corresponded to the repetition rate of 416.7 GHz . The dotted lines in the figures are the simulated ones. For simulation the temporal shape of the input pulse was assumed to be Gaussian having a pulse width of 0.6 ps . Both curves, measured and simulated, are well matched each other, especially in the amount of the time delays.

The contrast of Fig. 3 is getting worse as the repetition period decreases. The main cause of the contrast degradation or signal to noise degradation is the decrease in the signal level. Since the proposed device is passive, the intensity of the multiplied signal becomes smaller with the multiplication number. It is noted that Fig. 3 was normalized with the intensity of the multiplied pulse. Therefore, the raising of the background level was not totally caused by the noise level increment. However, we can think of several sources that might degrade the system performance. One is the temporal shape of the input pulse. Even though, in simulation the temporal shape of the input pulse was assumed to be Gaussian, the actual pulse shape is believed to have small side lobes caused by cavity modes of the figure-eight fiber laser, which can be verified from the side wing in the circle of Fig. 3 (a). The limited bandwidth of the LPG can cause some degradation. The fiber laser had an optical pulse width (FWHM) of about 6 nm in the wavelength domain and the LPGs had the 3-dB bandwidths wider than 20 nm as shown in Fig. 2 (a). Thus we expect that even though the temporal shape of the optical pulse is affected by the limited bandwidth of the LPG, it might be negligible. Another cause of the degradation might be found in the uniformity among the LPGs. Even though the LPGs were designed to have the same coupling strengths, there might be some fabrication

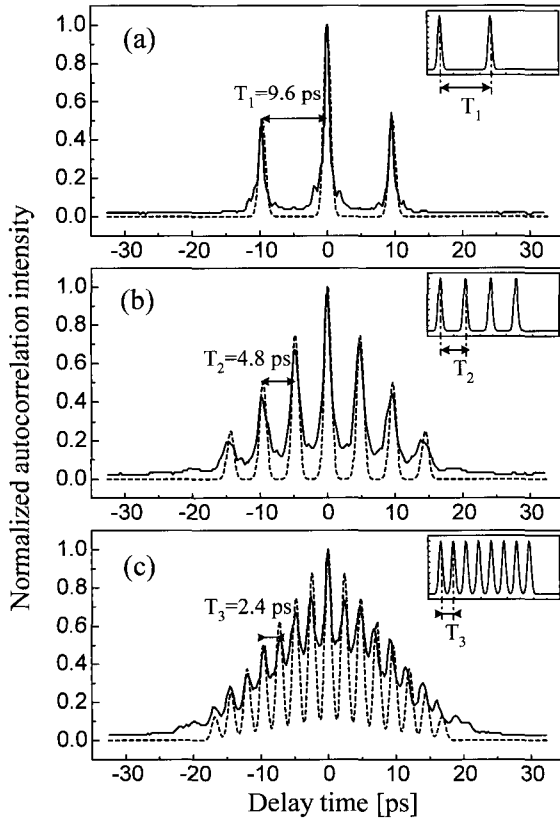


FIG. 3. Normalized autocorrelation traces of the pulse trains after (a) two-time (a repetition period T_1 of 9.6 ps), (b) four-time (T_2 of 4.8 ps), and (c) eight-time (T_3 of 2.4 ps) multiplications through the cascaded LPGs.

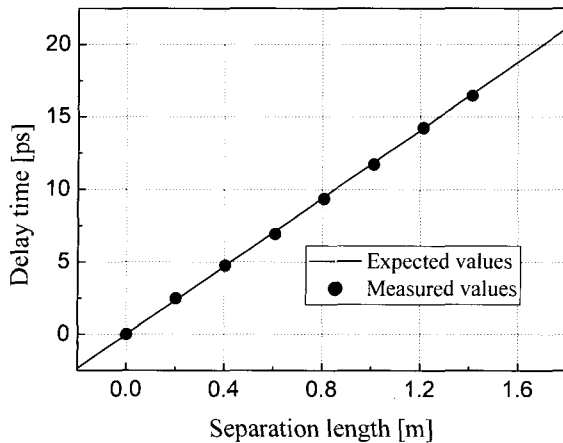


FIG. 4. Variation of the delay time plotted with respect to the route length. The data was obtained by analyzing the trace of Fig. 3(c). The solid line is the simulated curve.

errors. To prevent the variation in the coupling ratio over the spectral range of the input pulse, we are studying a method that can flatten the coupling ratio of the LPG by utilizing a specially designed optical fiber [12].

As shown in Fig. 3(c), the three delay elements generated four pulses. It can also be interpreted as four different routes of the pulses. Each route has a different length determined by the combination among the lengths of all delay elements. In Fig. 4, the time delays measured from Fig. 3 (c) were plotted with respect to the corresponding route length. For an example, the data point located near 1 meter is generated by the pulse that has propagated along the claddings of the delay elements 1 and 3. The longer route length gives the longer delay time. The solid line of the figure is the simulated curve obtained from Eq. (1). The maximum discrepancy between the measured and the simulated delay times is about 0.18 ps, which is small enough to be used for OTDM systems and optical code-division multiplexing access (OCDMA) systems [13,14].

IV. CONCLUSION

We have proposed and demonstrated the multiplier for ultra-short optical pulse trains by utilizing cascaded long-period fiber gratings. We have implemented eight-time multiplication with a repetition rate of 416.7 GHz ($T_3 = 2.4$ ps) with three delay-elements ($L_1 = 808.68$ mm, $L_2 = 404.34$ mm, and $L_3 = 202.17$ mm). Each delay element consisted of two LPGs and doubled the number of pulses. By adjusting the separations among the gratings the amount of time delay could be adjusted. The proposed technique is believed to provide a simple and convenient way for pulse multiplication

in high-speed OTDM applications and improve the fabrication accuracy of the device remarkably.

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