# Theoretical Analysis of High-Repetition Rate Optical-Pulse Multiplication Using Fiber-Coupler Loop Configuration

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***Abstract*— A new approach to generate ultrahigh-repetition rate optical pulses is proposed and analyzed theoretically. It is different from conventional approaches, which use fiber or integrated waveguide delay line circuits. The high-repetition-rate optical-pulse multiplication phenomenon occurs when the optical pulse's spectral width is greater than the transfer bandwidth of the coupler used. From the analysis, pulse doubling at repetition rates beyond the hundred-GHz range can be achieved using an all-fiber low-loss wavelength-division coupler with a looped end. The output repetition rate can be controlled by using fiber couplers with different equivalent transfer bandwidths.**

## I. Introduction

With the recent development of the ultrahigh-speed (>100 Gb/s) optical time-division multiplexed (OTDM) systems [1], high-repetition rate (>100 GHz) optical-pulse stream generation is necessary. Since such high-repetition rate is hard to obtain from semiconductor laser diodes or modelocked lasers, optical-pulse multiplication is necessary to generate a high-repetition rate optical-pulse stream from a lower rate stream. The approach of using fiber delay lines is not desirable, since it is difficult to control the relative fiber-delay length during fiber splicing. One solution is to use planar lightwave circuit (PLC) [2], with the expense of higher insertion loss and complexity. In [3], a Mach–Zehnder interferometer is used to generate multiple pulses for CDMA encoders/decoders. When the optical pulse's spectral width is greater than the transfer bandwidth characteristics of the coupler used, the repetition rate of the pulse train may be increased. That is, single pulse input may result in multiple pulses output [4]. In this letter, we have studied this phenomenon theoretically and proposed a novel and simple scheme using fiber-based couplers to achieve high-repetition rate optical-pulse multiplication.

## II. Single Coupler Loop Configuration

A simple fiber-loop configuration is shown in Fig. 1. The $2 \times 2$ coupler used is a 3-dB, symmetric, and polarization-independent single-mode fiber coupler. The sinusoidal spectral transfer characteristics [5], [6] of such coupler is given by

$$[C] = \sqrt{\beta}\begin{bmatrix}\cos(\frac{\pi f}{\Delta f}) & j\sin(\frac{\pi f}{\Delta f})\\ j\sin(\frac{\pi f}{\Delta f}) & \cos(\frac{\pi f}{\Delta f})\end{bmatrix} \tag{1}$$

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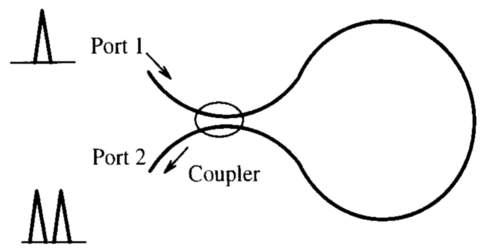

Fig. 1. Simple fiber loop configuration.

where $\beta$ is the coupler excess loss, $f$ is optical frequency, and $\Delta f$ is the equivalent optical frequency spacing of half of the channel spacing of the coupler.

After entering the loop at port 1, an optical pulse is split into two counter-propagating pulses inside the fiber loop and then passed through the same coupler again. Since the fiber loop is usually short (<1 m), it is assumed that fiber birefringence is negligible. The overall spectral transfer characteristics of such simple fiber loop is

$$\begin{aligned}[T] = \begin{bmatrix}T_{11} & T_{21}\\ T_{12} & T_{22}\end{bmatrix} &= [C]\begin{bmatrix}0 & 1\\ 1 & 0\end{bmatrix}[C]e^{j\phi}\\ &= \beta\begin{bmatrix}j\sin(\frac{2\pi f}{\Delta f}) & \cos(\frac{2\pi f}{\Delta f})\\ \cos(\frac{2\pi f}{\Delta f}) & j\sin(\frac{2\pi f}{\Delta f})\end{bmatrix}e^{j\phi}\end{aligned} \tag{2}$$

where $T_{ij}$ is the transfer coefficient in frequency domain from port $i$ to port $j$, and $\phi$ is the phase shift induced inside the fiber loop.

Consider when an input pulse $X_{\text{in}}$ (in frequency domain) enters the loop at port 1, the output from port 2 in frequency domain is $X_{\text{out}} = T_{12} \cdot X_{\text{in}}$. By taking the inverse Fourier transform, the temporal output will be

$$\begin{aligned}x_{\text{out}} &= t_{12} * x_{\text{in}}\\ &= [\delta(t-\tau) + \delta(t+\tau)] * \left(\frac{x_{\text{in}} * D}{2}\right)\end{aligned} \tag{3}$$

where $\tau = \frac{1}{\Delta f}$, $D$ is the pulse broadening function due to dispersion, $\delta(\cdot)$ is the delta function and $*$ is the convolution operation. If the length of the fiber loop is short, fiber dispersion $D$ is negligible. If the input pulse has a bandwidth larger than $\Delta f$, more than one pulses at port 2 will be obtained; otherwise, only one pulse will be obtained as illustrated in Fig. 2. In Fig. 3, with coupler's $\Delta f$ = 8 nm and input pulse width (FWHM) = 10 ps (or spectral width = 0.8 nm @1.55 $\mu$m), only one pulse is obtained at port 2.

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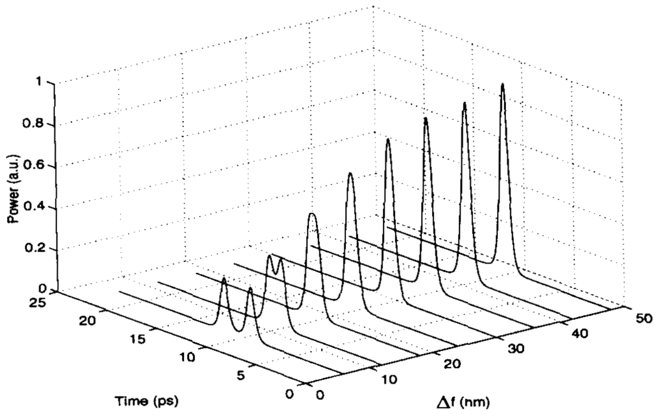


Fig. 2. Output optical pulse with signle 3-dB coupler against different $\Delta f$ with input-pulse width = 1 ps.

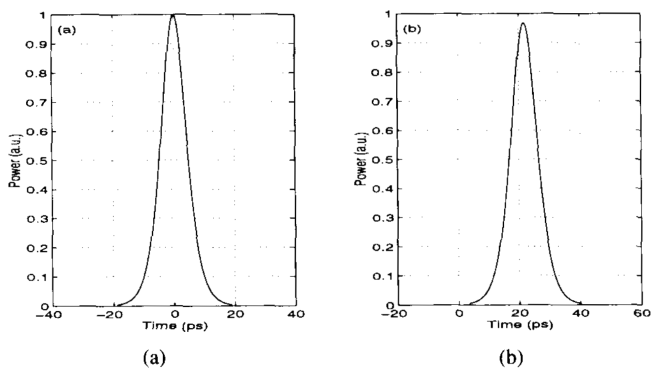


Fig. 3. (a) Input pulse with pulse width = 10 ps, and (b) output pulse after single coupler loop with $\Delta f$ = 8 nm.

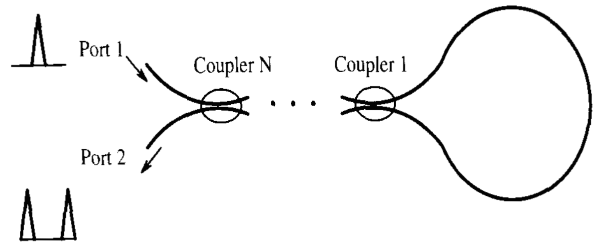


Fig. 4. Multiple cascaded coupler loop configuration.

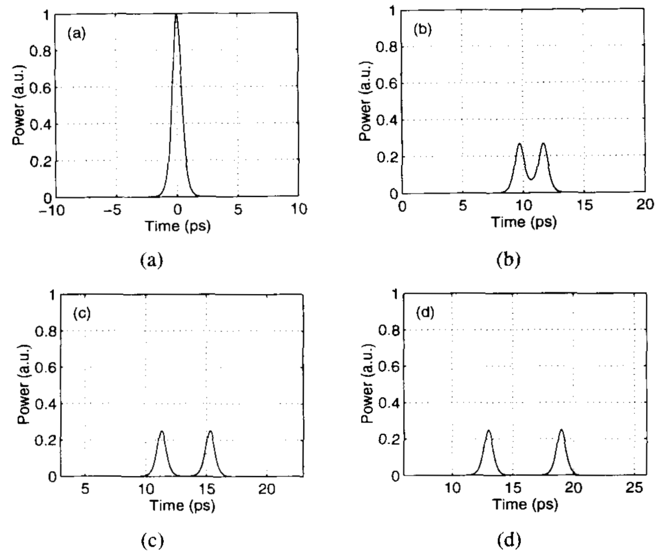


Fig. 5. (a) Input-optical pulse with 1-ps pulse width. Output-optical pulse with (b) single, (c) two, and (d) three cascaded identical 3-dB couplers, each with $\Delta f$ = 8 nm.

On the other hand, in Fig. 5(b), using the same 3-dB coupler, but with a 1 ps (or spectral width = 8 nm @1.55 $\mu$m) input pulse, two output pulses each with halved amplitude or one-fourth power and separated by $\frac{2}{\Delta f}$ are obtained. To have equal time spacing between adjacent pulses, the input pulse separation should be $\frac{4}{\Delta f}$, provided that the input pulse width is sufficiently narrow. Therefore, the repetition rate is doubled. For instance, a 250 GHz input pulse stream gives a 500 GHz output pulse stream for $\Delta f = 8$ nm.

From the above analysis, it is worth noting that the smaller the $\Delta f$, the lower the output-repetition rate. In next section, we show that by using more than one coupler cascaded in series together with a fiber loop, a narrow-band wavelength-division coupler can be realized and the ultrahigh output-repetition rate is controllable. Analysis and limitations of the cascaded coupler loop approach are also given for the case when the couplers are not identical.

## III. Cascaded Coupler Loop Configuration

For $N$ identical couplers as depicted in Fig. 4, the overall transfer matrix in frequency domain is

$$\begin{aligned}[T] &= \beta^N [C]^N \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} [C]^N e^{j\phi} \\ &= \beta^N \begin{bmatrix} j\sin(\frac{2N\pi f}{\Delta f}) & \cos(\frac{2N\pi f}{\Delta f}) \\ \cos(\frac{2N\pi f}{\Delta f}) & j\sin(\frac{2N\pi f}{\Delta f}) \end{bmatrix} e^{j\phi}. \end{aligned} \tag{4}$$

Therefore, at port 2, pulse separation is increased to $(\frac{2N}{\Delta f})$. For example, Fig. 5(c) and (d) show the case when two and three couplers are cascaded in series and the coupler's two lead lengths are perfectly matched. Notice the output pulse separation is increased.

In practice, $\Delta f_i$ (for $i = 1 \cdots N$) of each coupler might be different. The overall transfer matrix can be derived and expressed in a fairly simple form

$$[T] = \beta^N \begin{bmatrix} j\sin(\frac{2\pi f}{F}) & \cos(\frac{2\pi f}{F}) \\ \cos(\frac{2\pi f}{F}) & j\sin(\frac{2\pi f}{F}) \end{bmatrix} e^{j\phi} \tag{5}$$

where $F$ is defined as the equivalent optical frequency channel spacing of the resultant sinusoidal spectral response and is given by

$$F = \frac{1}{\frac{1}{\Delta f_1} + \cdots + \frac{1}{\Delta f_N}}. \tag{6}$$

Therefore, the output pulse separation will be $(\frac{2}{F})$. Knowing these properties, the output pulse separation can be changed by using different number of couplers or coupler with different resultant $F$. From (2), (5), and (6), the resultant transfer characteristics are equivalent to a wavelength-division multiplexer (WDM) [6], [7] with narrower channel spacing.

To have pulse-multiplication effects, the following condition should be satisfied as a rule of thumb:

$$\frac{1}{F} \geq W \geq 2 \sum_{i=1}^{(N-1)} \left(\frac{d_i}{c}\right) \tag{7}$$

where $d_i$ is the length difference of the two coupler leads between the $i$th and the $(i+1)$th couplers, $c$ is the velocity of light in the fiber, and $W$ is the input pulse width (FWHM). For example, for six cascaded couplers @ 1550 nm with $\Delta f_i \approx$ 7 nm for $i = 1, \cdots, 6$, using equation (6), the resultant $F$ is about 1.17 nm. The output-repetition rate about is 73 GHz. The maximum input pulse width allowed is 6.85 ps and the total length matching tolerance is 0.7 mm. One possibility to realize the cascaded couplers with such accuracy is to make several fusion points on two adjacent fibers. Notice that the length accuracy requirement is reduced as the pulse separation is increased. The cascaded coupler loop scheme serves as an alternative of using fiber delay lines for optical-pulse multiplication at ultrahigh-repetition rate, since both approaches require high-fiber length accuracy. One major difference is that the pulse-separation time only depends on the value of $F$ for the proposed scheme.

## IV. Discussion

The proposed high-repetition rate optical-pulse multiplication scheme is quite simple. It only uses fiber-based couplers, which have much less insertion loss than the PLC though still half of the power is lost (which is similar to the case of fiber delay line). High-repetition rate pulse multiplication can be achieved with a single coupler, as in Fig. 1, without the coupler lead-length matching problem, provided that the pulse-multiplication conditions are met. By cascading different number of couplers in series, optical-pulse streams of different output pulse separations can be obtained with the expense of increased complexity. This feature offers the flexibility and controllability over the pulse separation of such optical-pulse multiplier.

Such a scheme is suitable for future ultrahigh-speed giga/terahertz TDM systems or narrow pulse-separation applications. It can be used as a high-repetition rate optical-pulse multiplier. Moreover, it can be used to generate the clock pulses for ultrahigh-speed multirate TDM, in which more than one time slot per frame is demultiplexed simultaneously. For instance, with a 250-GHz input repetition-rate optical-data stream, two time slots can be demultiplexed simultaneously by using the multirate clock, as shown in Fig. 6.

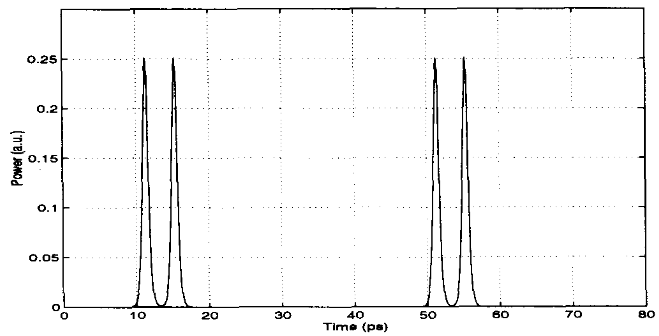


Fig. 6. Multirate optical-clock generation with single 3-dB coupler of $\Delta f =$ 8 nm, input-pulse width = 1 ps and input-repetition rate 250 GHz.

## V. Conclusion

A new approach to generate ultrahigh-repetition rate optical-pulse stream is presented and analyzed theoretically. The proposed scheme allows pulse multiplication with very short-pulse separation without using PLC. Pulse separation can be further controlled by using a coupler with different $\Delta f$ or different number of couplers. It is suitable as high-repetition rate (>100 GHz) pulse multipliers in ultrahigh-speed optical-TDM transmission systems.

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