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# Dispersion-free Tunable Optical Delay Using Optical Fourier Transformation

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***Abstract*— This paper describes a dispersion-free tunable optical delay using Optical Fourier Transformation (OFT) method. Tunable optical delay is based on the combination of wavelength conversion and dispersion. By means of OFT, dispersion in the delayed output signal is eliminated. Principle of dispersion-free property of OFT for optical delay is well-explained. Moreover, analytical results present the effectiveness of the use of OFT for dispersion-free optical delay. A continuously tunable delay up to 1000-ps is shown for the 20-ps input signal.**

***Keywords*— Tunable optical delay, fiber dispersion, optical Fourier transformation, wavelength conversion, fiber optics communication**

## I. Introduction

In ultra-high speed optical communication networks, data is carried from a source to destination in optical format without any optical-to-electrical (O/E) and electrical-to-optical (E/O) conversion. Such O/E/O conversion of information is a bottleneck for increasing data transmission rate. Thus, it is desirable to have all-optical components (with no need for O/E/O conversion) to transfer data optically. One such component is an all-optical buffer which is a key building block for the realization of routers for all-optical packet switching networks. Recently, much attention has been given to the research on all-optical delays for implementing optical buffers. All-optical delays can be used for accurate optical timing in time multiplexing, data packet synchronization, switching, time-slot interchange [1] and optical control of phase array antennas for radio frequency communication [2].

Many researches on optical delays have been carried out utilizing: 1) slow light technique and 2) combination of arbitrary wavelength translation and the group velocity dispersion (GVD) [3]. The latter is a popular technique in which the wavelength of the signal is converted to a different one and after passing through the optical fiber, due to the chromatic dependence of the signal group velocity in the fiber, the signal with different wavelength travels in different speed [4] and hence optical delay can be realized. However, in this technique since the optical signal has to pass through the dispersive fiber, the waveform of the output signal after the optical delay is dispersed in time which is an unwanted effect that degrades transmission performance. Therefore, realization of dispersion-free optical delay is very much desirable. Irfan Fazal [5] and Yan Wang [6] demonstrated dispersion-free optical delay by adding a dispersion compensator after the optical delay module.

In this paper, dispersion-free tunable optical delay using Optical Fourier Transformation (OFT) method is proposed. The principle of dispersion-free tunable optical delay using OFT is described and analytical results that demonstrate an optical delay with the elimination of dispersion are presented.

## II. Principle of Dispersion-free Tunable Optical Delay using OFT

### A. A Tunable Optical Delay without OFT

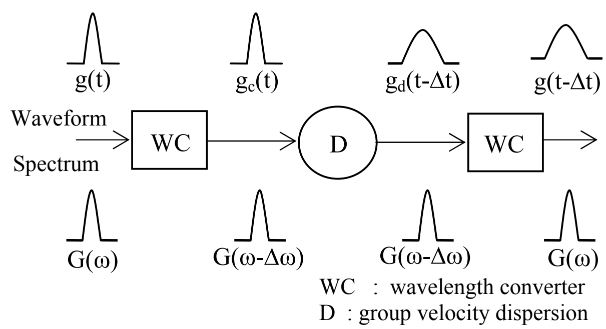



Fig. 1 A tunable optical delay without OFT

Fig. 1 shows a tunable optical delay without using OFT. Optical delay is formed by the combination of wavelength conversion and dispersion. The input signal is converted to a higher wavelength (i.e. a lower frequency) and passed through the dispersive optical fiber with length L. Due to chromatic dependence of the fiber, the converted signal with a lower frequency $G(\omega-\Delta\omega)$ travels slower than the original input signal. Thus, the total delay $\Delta t$ is the product of wavelength conversion width $\Delta\omega$ and group velocity dispersion D. This phenomenon can easily be understood from the following equation:

$$\Delta t = \Delta\omega . D \quad (1)$$

where $D = \beta_2.L$ is the group velocity dispersion of the optical fiber. By changing $\Delta\omega$, various delay values can be obtained and hence it is called a tunable delay. After the dispersive fiber, there is another wavelength converter to restore the original wavelength G(ω).

As seen in Fig. 1, in this technique the waveform after the optical delay is dispersed in time (i.e. pulsewidth of the signal becomes wider) because of the dispersion effect of the optical fiber. Therefore, after leaving the delay module, in further transmission process, the quality of this distorted signal becomes reduced and its transmission performance is degraded. However, it should be noted that spectrum of the signal remains unchanged.

### B. *Dispersion-free Tunable Optical Delay with OFT*

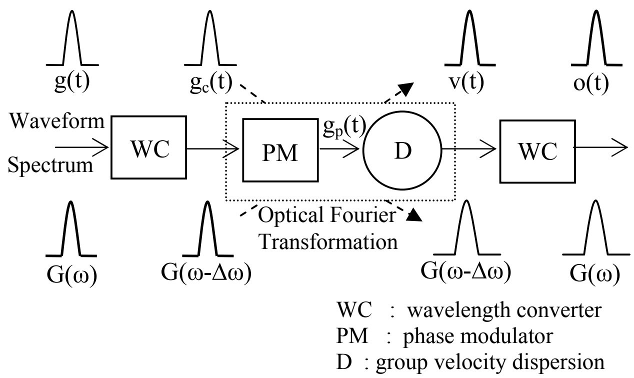



Fig. 2 Dispersion-free tunable optical delay with OFT

Fig. 2 shows the operation of a dispersion-free tunable optical delay using OFT technique. In contrast to the previous method, here in this proposed method, optical Fourier transformation (OFT) technique is utilized. OFT is transformation from frequency to time domain or vice versa. In Fig 1, it should be noted that although waveform of the signal is dispersed in time domain, its spectral profile is completely maintained. So, if one can convert spectral profile of the transmitted signal into the waveform in time domain, then there is always no dispersion in the output signal.

As shown in Fig.2, by means of OFT, the input waveform $g_c(t)$ is converted to frequency domain and undistorted input spectrum G(ω-Δω) is translated to the output waveform in time domain. Thus, there is no dispersion in the delayed output signal v(t).

## III. Implementation of OFT

OFT can be achieved by applying a linear frequency chirp (parabolic phase shift) using a phase modulator PM followed by an appropriate GVD medium [7] as shown in Fig. 2. After the first wavelength converter, the transmitted signal becomes

$$g_c(t) = g(t)\exp(j\Delta\omega t) \tag{2}$$

This converted signal is passed through the phase modulator. When the chirp rate by PM is C, the chirped pulse is written as

$$g_p(t) = g_c(t)\exp(-j\frac{1}{2}C\,t^2) \tag{3}$$

The linearly chirped pulse is then passed through GVD medium. The delay v(t) is given by the convolution between $g_p(t)$ and the dispersion and is expressed as

$$v(t) = \sqrt{\frac{1}{j2\pi D}}\int_{-\infty}^{\infty} g_p(\tau)\exp[\frac{j}{2D}(t-\tau)^2]d\tau \tag{4}$$

which can be rewritten in the following form when D = 1/C:

$$v(t) = \sqrt{\frac{1}{j2\pi D}}\exp(j\frac{1}{2}C\,t^2)\int_{-\infty}^{\infty} g_p(\tau)\exp[-j(\frac{t}{D}-\Delta\omega)\tau]\,d\tau \tag{5}$$

Since ω = t/D, where D determines the transformation ratio between the frequency and time domains, equation (5) can be stated as

$$v(t) = \sqrt{\frac{1}{j2\pi D}}\exp(j\frac{1}{2}C\,t^2)\int_{-\infty}^{\infty} g_p(\tau)\exp[-j(\omega-\Delta\omega)\tau]\,d\tau$$

$$= \sqrt{\frac{1}{j2\pi D}}\exp(j\frac{1}{2}C\,t^2)\;\;G(\omega-\Delta\omega) \tag{6}$$

Equation (6) indicates that the output waveform after OFT is proportional to the input spectrum G(ω-Δω). Again, when we take ω = Ct and Δω = CΔt, it can be rewritten as

$$v(t) = \sqrt{\frac{1}{j2\pi D}}\exp(j\frac{1}{2}C\,t^2)\;\;G\,[\,C(t-\Delta t)\,]$$

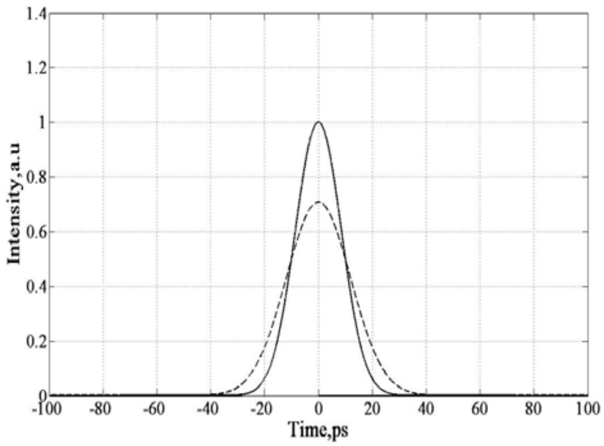
$$= \sqrt{\frac{1}{j2\pi D}}\exp(j\frac{1}{2}C\,t^2)\;\;g(t-\Delta t) \tag{7}$$

According to equation (7), it can easily be understood that the output signal v(t) after OFT is delayed by Δt with respect to the input signal g(t) and is dispersion-free since it is proportional to the input spectrum as indicated by equation (6).

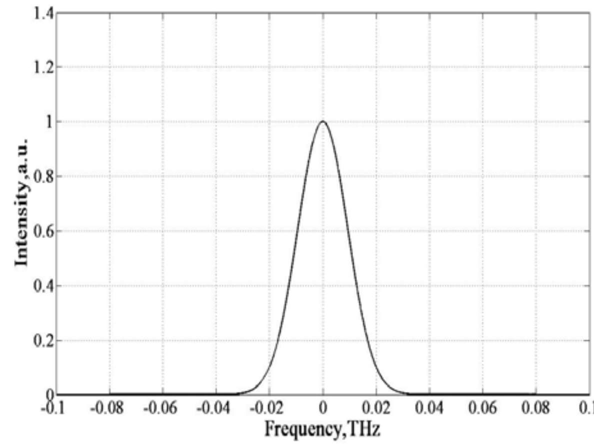
The second wavelength converter in Fig.2 restores the wavelength or frequency of the delayed signal v(t) to the original state G(ω). Therefore, final output signal o(t) with the original input frequency is dispersion-free and delayed by Δt.

## IV. Analytical Results

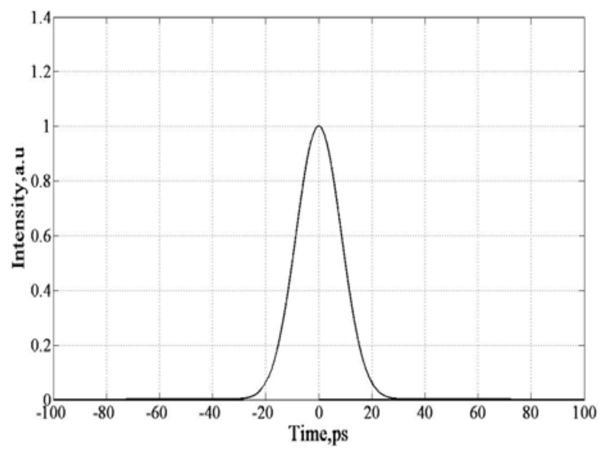
To evaluate the effectiveness of the proposed method, some numerical simulations were carried out to show the elimination of dispersion in the delayed output signal. For the simulation, 20-ps Gaussian pulse is taken as input. When the frequency-time transformation ratio D is set to be $(20/1.665)^2$, the envelope of delayed output signal becomes the same as the input. Then, chirp rate by the phase modulator is C = 1/D = 0.00693 $ps^{-2}$. Thus, single mode fiber with $\beta_2$ = -20 $ps^2/km$ and the length L = 7.2145 km has to be used.



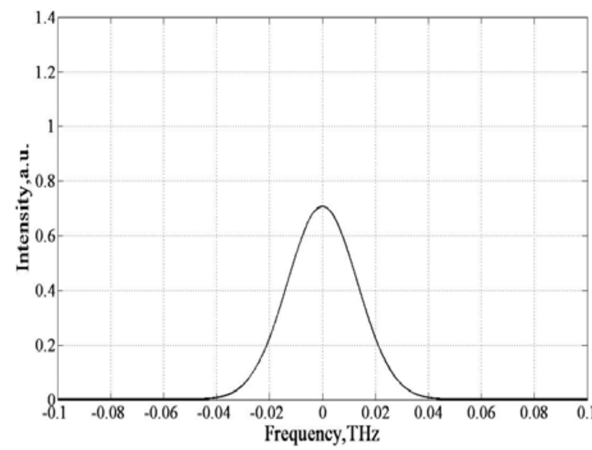

(a-1)



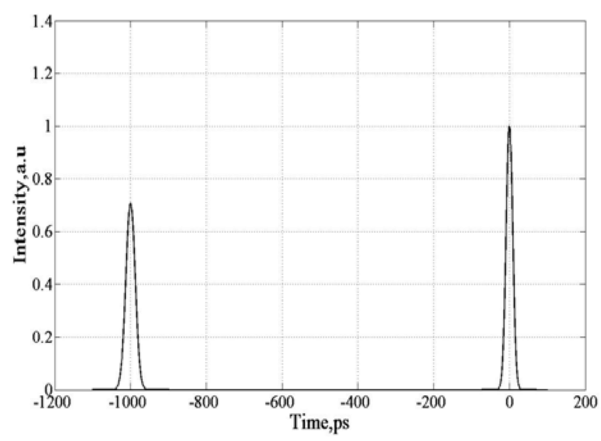

(a-2)



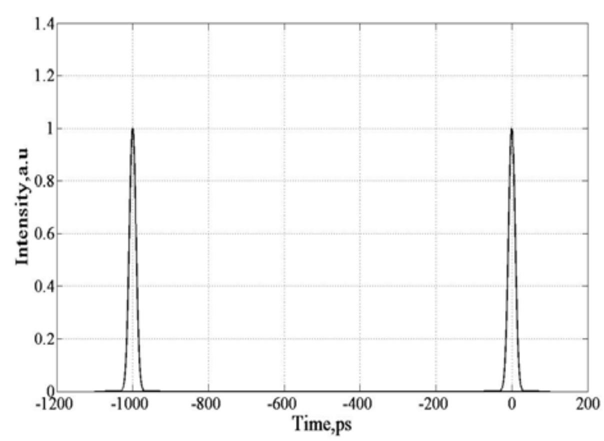

(b-1)




(b-2)




(c-1)




(c-2)

Fig. 3 (a-1) Input waveform (solid curve) and delay waveform without OFT (dotted curve). (b-1) Delay waveform with OFT (Both delay waveforms are referenced at Time = 0 for simplicity). (a-2) and (b-2) are spectral profiles corresponding to (a-1) and (b-1) respectively (Spectral profiles for delay signals are referenced at Frequency = 0 for simplicity). (c-1) Dispersed delay signal at t = -1000 ps and the input [True time scale for the waveforms in (a-1)]. (c-2) Dispersion-free delay signal at t = -1000 ps and the input [True time scale for the waveform in (b-1)].

Fig. 3 (a-1) shows the 20-ps input signal and the delay signal after the delay module without OFT. Delay pulse is broadening because of the dispersion effect in Fig. 3 (a-1), but the transmitted spectral profile seen in Fig. 3 (a-2) is the same as that of the input. After passing through the delay module with OFT, delay pulse completely recovers its original width as shown in Fig. 3 (b-1), whereas its corresponding spectrum is broadened because of chirping by the phase modulator as seen in Fig. 3 (b-2).

In this simulation, the final output signal after the delay module is calculated to be delayed by 1000-ps which can be determined by choosing appropriate $\Delta\omega$ values as indicated by equation (1). In this paper, wavelength converters have not been implemented, and hence a suitable value of $\Delta\omega = 6.93$ is simply chosen for the required delay. By changing $\Delta\omega$, a tunable optical delay can be obtained.

Fig 3(c-1) shows a 1000-ps delay with dispersion when OFT technique is not used in the optical delay module, while a dispersion-free 1000-ps delay is obtained in Fig 3(c-2) when OFT is utilized in the proposed method.

## V. Conclusions

A 1000-ps dispersion-free tunable optical delay using OFT technique has been demonstrated. The delay module is based on the wavelength conversion and dispersion. By means of OFT, the dispersion occurred in the output delay signal is eliminated. OFT is implemented using linear frequency chirp (i.e. parabolic phase shift) by the phase modulator and the appropriate GVD medium (i.e. optical fiber with suitable length). By changing $\Delta\omega$, various delay values can be obtained. In this paper, wavelength conversions $\Delta\omega$ have not been implemented. However, in fact the range of $\Delta\omega$ will be limited by the wavelength conversion method. Numerical simulations have also been carried out to prove that by means of the proposed method, dispersion-free tunable optical delay can be achieved successfully. Therefore, in conclusion, OFT-based optical delay module will be very useful in optical signal processing because of its dispersion-free property.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