Quadrupling Optical Delay Range Using Polarization Properties

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***Abstract*—We describe a scheme to quadruple an optical delay using polarization properties of light in a fiber and demonstrate a fast variable delay line with a record-setting delay range of 72 mm at a speed of ~2 kHz (corresponding to ~136 m/s). The method can find various applications where a large optical delay or a high-speed delay variation is required, including optical coherent tomography, optoelectronic oscillator, programmable optical delay lines, and optical delay buffers.**

***Index Terms*—Delay line, fiber optics, optical coherence tomography, polarization.**

I. Introduction

In MANY applications, such as in an optoelectronic oscillator (OEO), large optic delay up to 10 km is required [1]–[3]. The optical delay can be increased by simply increasing the fiber length. However, such a method also increases the size and cost of the fiber coil. In other applications, such as time-domain optical coherence tomography (TD-OCT), large and fast optical delay change is a must [4]–[6]. Unfortunately, it is difficult in practice to make a large delay change while keeping the delay change rate sufficiently high. In some OCT applications, a delay changing length of up to 10 mm with a changing rate up to 10 kHz is desired [7]–[9].

It is well known and widely used to double the fiber delay or delay change simply by using a mirror or Faraday mirror without increasing fiber length. Such a configuration is often used in a conventional TD-OCT system in which the delay change produced by a variable delay line automatically doubled. A method for multiplying the fiber delay or delay change more than two times has been proposed [10] by using polarization manipulation in free-space, with limited range and speed. Other methods include bouncing a light beam back and forth in an optical cavity either in free space or in an optical fiber. The fiber-cavity-based delays suffer from resonant frequency filtering effect and cannot be used for applications requiring large bandwidth, such as OCT. The free-space cavity-based delay can avoid resonant filtering effect; however, the delay range and delay changing speed are limited.

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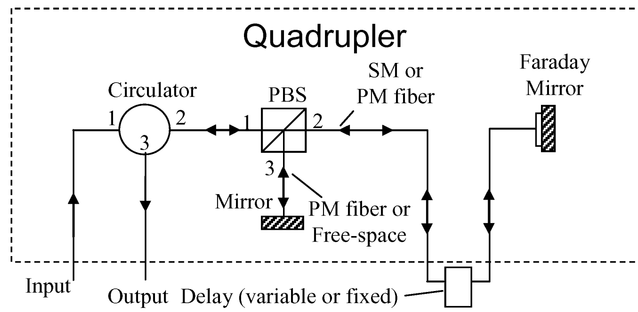

Fig. 1. Configuration of a delay quadrupler: the optical path is quadrupled by going through the delay medium (variable or fixed) four times.

In this letter, we describe an apparatus to quadruple the signal delay in an optical fiber without increasing the fiber length. With the delay quadrupler and a fiber stretcher, we achieve an unprecedented 72-mm delay at a rate of ~2 kHz (or ~136-m/s), the largest delay variation rate reported to the best of the authors' knowledge.

II. Concept Description

The concept of the delay quadrupler is shown in Fig. 1. The input light signal first passes through a polarization beam splitter (PBS) from Ports 1 to 2 before entering the delay fiber. A Faraday mirror is placed at the end of the delay fiber to reflect the light signal back to the PBS, and cause the light to travel through the delay fiber twice. Because of the ortho-conjugate property of the Faraday mirror, the state of polarization (SOP) of the reflected light is always orthogonal to the forward going beam at every point along the fiber. Therefore, at the PBS, the SOP of the reflected signal is orthogonal to that of the forward going light and hence all light signals will be directed to the Port 3 of the PBS.

A mirror is placed at the end of Port 3 to reflect the light back to the PBS without changing its SOP. The mirror can be directly attached to Port 3 or can be separated from the PBS with a medium, such as a polarization-maintaining fiber or a free-space, as long as not to alter the SOP. The reflected light from the mirror is then directed back to the delay fiber by the PBS, which causes the light to travel through the delay fiber the third time. After hitting the Faraday mirror the second time, the light will be reflected back towards the PBS the second time, which causes the light to travel through the delay fiber the fourth time. At the PBS, the SOP of the twice-reflected light by the Faraday mirror is the same as that of the input light and will be directed back to the input port (Port 1) of the PBS. Therefore, the light passes the delay fiber totally four times before exiting the PBS. An optical circulator can be used to separate the input and the output light. The loss of such a scheme (without the delay

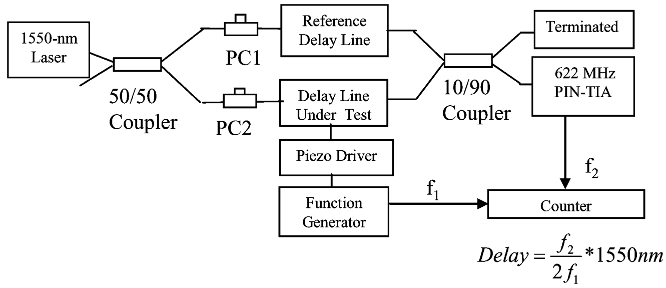

Fig. 2. Concept verification setup (Mach–Zehnder interferometer configuration) to measure the generated delay. PC: polarization controller. PIN-TIA: InGaAs PIN and transimpedance amplifier.

line) is estimated as ~2 dB, considering the insertion losses of the circulator, PBS, and Faraday mirror. Note that the polarization-dependency of the scheme requires a well-controlled polarization state along the signal path to guarantee the desired performance.

For applications where only the delay change matters, the delay fiber can be replaced with a variable delay, as shown in Fig. 1. With this configuration, any delay change is also amplified four times. All components can be enclosed in an enclosure (shown with dotted lines), except that the delay fiber or the variable delay can be placed outside the enclosure to easily change to different delays. Please note that the bandwidth of the above configuration is extremely wide, only limited by the Faraday mirror and the circulator.

III. Experimental Verification

To verify the concept of the delay quadruple, we construct a Mach–Zehnder interferometer, as shown in Fig. 2. A distributed-feedback (DFB) laser at 1550 nm is first split into two paths by a 50/50 fiber coupler. The reference path contains a manual polarization controller PC1 and a reference delay line. The testing path contains a second polarization controller PC2 and a delay line under test. The two paths are then recombined by a 10/90 fiber coupler. PC1 is used to align the polarization state in the reference path to be the same as that in the testing path at the signal combining coupler and the reference delay line is used to balance the optical delay path difference between the two paths to be less than the coherence length of the DFB laser.

For TD-OCT applications, we specially design a high-speed fiber stretcher driven by a piezoelectric actuator (PZT). Such a fiber stretcher is capable of generating a delay variation of 18 mm at a resonant frequency around 2 kHz [11]. This is also the largest delay range reported at such a high frequency, a desired feature for dental OCT applications where large delay variations at high speed is required. We use this device in the experiment to verify the quadrupling concept.

To test fast delay variations, we count interference fringes of the interferometer of Fig. 2 using a frequency counter. Each interference fringe corresponds to a delay variation of a wavelength (1550 nm in this case). In the setup, we use a sinusoidal wave signal with a frequency f_1 from a function generator to drive the fiber stretcher. The same driving signal is also used as a reference for the frequency counter. A high-speed detector is used to detect the interference signal and the output is fed into

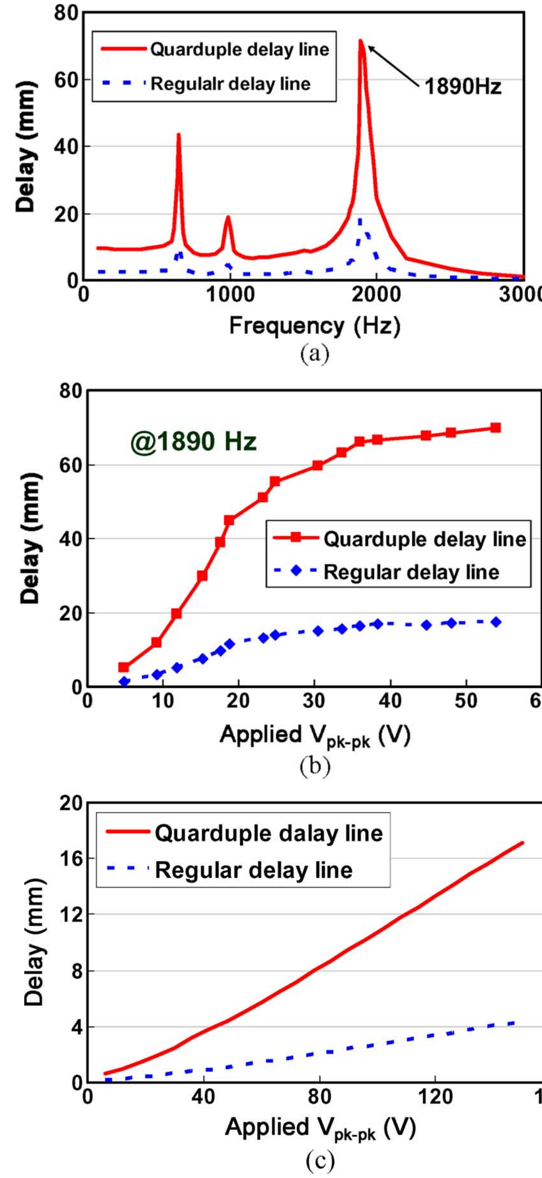

Fig. 3. Experimental results of the delay quadrupler. (a) Delay range as a function of frequency of a fiber stretcher. The voltage applied to the PZT is 55 V. (b) Delay range as a function of applied voltage on the fiber stretcher at the resonant frequency (~1890 Hz). (c) Delay range as a function of applied voltage at 100 Hz. In all the graphs, the dashed line is the delay of the fiber stretcher itself and the solid line is the quadrupled delay range.

the frequency counter to measure the frequency of the interference signal. Assume that the interference signal has a frequency of f_2, the delay range T in micrometers can be calculated as

$$T = \frac{\lambda f_2}{2f_1} = \frac{1.55 f_2}{2f_1}. \quad (1)$$

We first directly insert the fiber stretcher into the setup as the "delay line under test" (Fig. 2) and measure delay variation range as a function of frequency and driving voltage. After that, we put the fiber stretcher into the delay quadrupler of Fig. 1 and insert the whole delay quadrupler into the setup as the "delay line under test" (Fig. 2) to measure delay variation range as a function of frequency and driving voltage.

The results are shown in Fig. 3(a)–(c). As can be seen, the delays are indeed increased four times for all driving frequencies

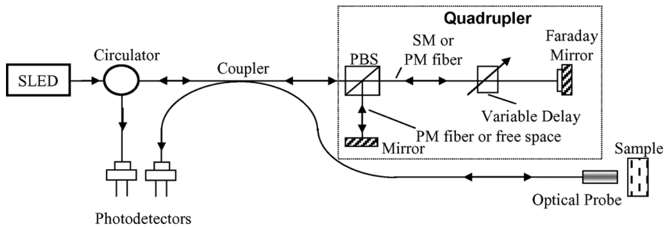

Fig. 4. Illustration of a delay quadrupler in a TD-OCT system to increase the delay variation range and the speed of the variable delay line.

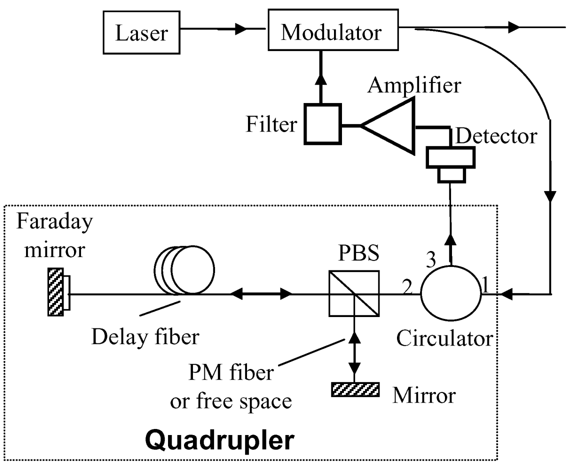

Fig. 5. Illustration of the $4\times$ delay multiplier used in an OEO application.

and driving voltages. It is important to notice that a large delay range of 72 mm is achieved at a resonant frequency of 1.89 kHz, which corresponds to a delay change rate of $\sim$136-m/s. Such a large delay range is sufficient for ophthalmic OCT application to cover the whole depth of an eye. It is also important to notice that the fiber stretcher itself without the delay quadrupler can generate a delay variation range of 18 mm at 1.89 kHz with only 55 V of applied voltage! The resonant frequency of the fiber stretcher can also be tuned to slightly above 2 kHz in the experiment. As pointed out, such a delay line is also ideal for dental OCT applications where a large delay at high frequency is required. Fig. 3(c) illustrates a generated delay at a low nonresonant frequency (i.e., 100 Hz) for applications that require better linearity but low speed.

As mentioned previously, the delay quadrupler can be used in an OCT system or a time-domain reflectometer to increase the delay range of a variable optical delay line and hence the measurement range of the system, as well as amplifying the delay variation at high speed, as shown in Fig. 4.

The delay multiplication scheme can also be used in an OEO to quadruple the total delay without increasing the fiber length, as shown in Fig. 5. In this application, not only the cost of the OEO is reduced, but also the size. Such a size reduction is of significant importance for making compact OEOs into real world applications [12].

Moreover, such a delay quadrupler can be used in dynamic optical networks, where tunable time delay lines are used as the bit stream synchronizer, optical buffers, etc. [13], [14].

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