Optical Fiber Recirculating Delay Line Incorporating a Fiber Grating Array

W. Zhang, J. A. R. Williams, and I. Bennion

Abstract—**For a practical optical fiber recirculating delay line the maximum notch depth and tunable free spectral range are difficult to achieve because of fixed coupling coefficient and loop length. We present here an optical fiber recirculating delay line incorporating a fiber grating array. In this work, the effect of insertion loss in the delay loop is investigated and used to maximize the notch depth of the frequency response. The tunable free spectral range is obtained from the wavelength dependent loop length introduced by the fiber grating array.**

Index Terms—**Fiber Bragg grating, microwave signal processing, optical fiber delay.**

I. Introduction

OPTICAL fiber microwave and millimeter wave signal processing has attracted many research interests since it can remove the bottleneck caused by conventional microwave electronic filter. Remarkably it is totally compatible with optical fiber microwave communication links, which allows carrying out microwave signal processing while signals are still in optical domain, thus allows overcoming the limitations of optoelectronic and electro-optic conversions for high speed signals. Most of optical fiber microwave and millimeter wave signal processing are based on optical fiber delay lines [1]–[5]. Optical fiber recirculating delay line is one of compact configurations and can provide a steeper notch response than a Mach–Zehnder notch filter. It can further be used to produce more complex filtering functions by topologically combining such basic units. In an optical fiber recirculating delay line the frequency response is controlled by the coupling coefficient of the coupler used and the length of the recirculating loop [1]. Due to the fact that the coupling coefficient of fiber optic coupler and the loop length generally are fixed, the frequency response of the recirculating delay line is not tunable, and the notch depth even more difficult to be maximized, which, however, is crucial to some applications. In this letter we propose an optical fiber recirculating structure incorporating a fiber grating array to achieve both maximum notch depth and tunable free spectral range.

II. Theory Background

A basic recirculating fiber-optic filter unit consists of a fiber coupler and a length of fiber to provide a delayed feedback optical signal. Since optical fiber delay line signal processing inco-

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The authors are with the Photonics Research Group, Aston University, Birmingham B4 7ET, U.K. (e-mail: w.zhang@aston.ac.uk).

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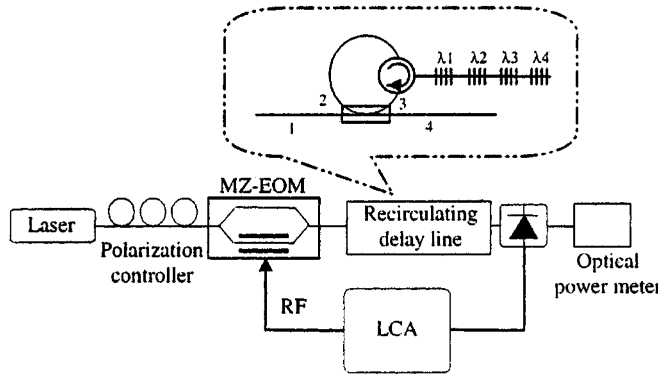
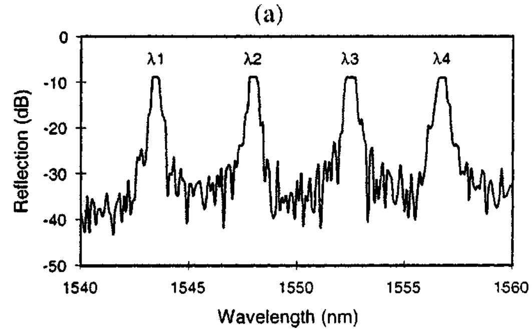


(a)



(b)

Fig. 1. (a) Optical fiber recirculating delay line and experimental arrangement and (b) the spectra of the fiber grating array.

herently combines tapped signals [1], the transfer function can be obtained by use of Z transform and expressed as [6]

$$H(Z) = \frac{(Z-2)\cdot K + 1}{Z - K} \tag{1}$$

where Z represents a delay unit for the light traversing along the fiber loop, K is defined as the coupling coefficient from the input port 1 to port 4, as illustrated in Fig. 1. Substituting $\exp(j\omega T)$ for Z in (1) will give the magnitude and phase response of the recirculating delay line, where T represents the unit delay of the recirculating loop. The theoretical notch depth maximizes at $K = 1/3$ where the transfer function has a zero on the unit circle of Z plane. The free spectral range (FSR) only depends on the loop length.

In a practical recirculating delay line the insertion loss is inevitable (for instance, induced by the splicing between the port *2* and 3, and the fiber coupler itself). After considering the insertion loss, signal via fiber loop will be attenuated by a factor

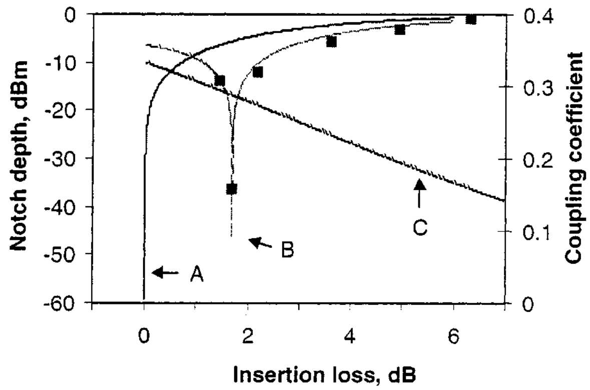


Fig. 2. Notch depth and coupling coefficient against insertion loss. Experimental data is obtained with an operating wavelength of 1543.6 nm and a loop length of 1.48 m.

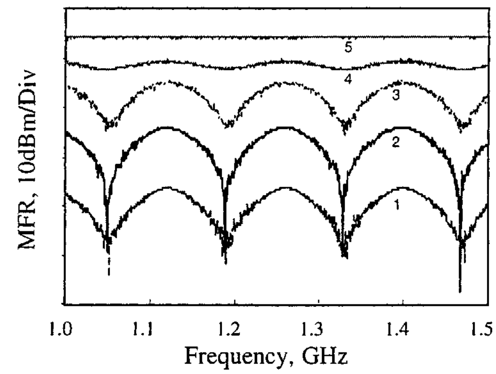


Fig. 3. Measured frequency responses under different insertion loss. Insertion loss from curve 1 to 5: 1.5 dB, 1.65 dB, 2.24 dB, 4.95 dB, and 6.4 dB.

of $\exp(-\alpha)$, where $\alpha = 0$ for zero insertion loss. The transfer function (1) can be rewritten as

$$H(Z) = \frac{[\exp(\alpha)Z - 2] \cdot K + 1}{\exp(\alpha)Z - K}. \quad (2)$$

Obviously when $K = 1/3$ the zero of the transfer function lie inside the unit circle rather than on it. This means the maximum notch depth no longer appears at $K = 1/3$. Since the FSR is only dependent on the loop length, all the notch frequencies are fixed for a certain loop length. Therefore we can get the notch depth by calculating the response level at a certain notch frequency. The theoretical variation of the notch depth of an optical fiber recirculating delay line over insertion loss for $K = 1/3$ is given as the curve A in Fig. 2. As can be seen that the maximum notch depth only appears when insertion loss is zero and reduces quickly with the increase of insertion loss. Therefore changing the insertion loss can reconfigure the frequency response.

Furthermore, from the (2) one can find that for an insertion loss there always exists a corresponding coupling coefficient K to make the zero on the unit circle of Z plane, in other word, to maximize the notch depth. Setting $Z = 1$ and the numerator of the (2) to zero one can find the condition for maximized notch depth, expressed as

$$\exp(\alpha) \cdot K + 2K - 1 = 0. \quad (3)$$

Therefore in the case of the insertion loss involved there always exists a coupling coefficient to maximize notch depth, as reported in [6]. On the other hand, one can always obtain the maximum notch depth by inducing an insertion loss α to satisfy (3), if the coupling coefficient is less than 1/3. The theoretical calculation of the relation between the insertion loss and coupling coefficient for maximum notch depth is shown as the curve C in Fig. 2. The curve B in Fig. 2 shows the relation of notch depth and insertion loss for a coupling coefficient of 0.24. From it one can notice that the maximum notch depth appears at the insertion loss of 1.68 dB.

III. Experiments and Results

An experimental arrangement was established to verify our theoretical prediction, shown in Fig. 1. A HP8703A lightwave component analyzer (LCA) was used for generation of the microwave modulating signal and its detection as well. A fiber coupler with coupling ratio of 24:76 was used to construct a recirculating delay line. To achieve tunable FSR, a fiber grating array was induced into the fiber loop. Since the fiber gratings work in reflection mode, a fiber circulator was used. The fiber grating array used in this work consists of 4 fiber Bragg gratings, each locating at different wavelength whose spectrum is shown in Fig. 1(b). A tunable laser was used as light source its wavelength was set at one of Bragg wavelength of the fiber grating array. Changing the operating wavelength gives a different loop length determined by the corresponding fiber grating thus a different FSR. Analyzing the optical signal exiting from the delay line gives its microwave frequency response.

Setting the laser wavelength at $\lambda 1$ gives rise to the loop length of 1.48 m. The measured frequency response of the delay line is shown as the curve 1 in Fig. 3. The corresponding notch depth was around -15 dB obviously not at its maximum. However we noticed that the introduction of the fiber circulator and the grating array brought in an insertion loss of $\sim$ 1.5 dB. According to the above theoretical analysis, the insertion loss inevitably affects the notch depth. For the coupling ratio of the fiber coupler used in this work the maximum notch depth appears at the insertion loss of 1.68 dB. Therefore an extra insertion loss was induced by slight bending of the fiber loop and measured with an optical power meter. Some typical frequency responses under different insertion loss were measured, and are shown in Fig. 3.

It can be seen that without bending the fiber loop the notch depth was only -15 dBm; the maximum was reached being -36.6 dBm at an extra insertion loss around 0.15 dB, shown as the curve 2 in Fig. 3. As the applied insertion loss increased, the notch depth reduced rapidly. At the insertion loss of 6.4 dB the frequency response devolved into almost a straight line (curve 5). The experimental data is depicted in Fig. 3 as well, to compare with the theoretical results (curve B). The good agreement between the measured data and the curve B was achieved.

Setting the laser wavelength to other grating wavelength can provide a tunable FSR. The measured frequency responses are shown in Fig. 4, from the top trace to the bottom trace corresponding to the loop length of 1.48 m, 2.02 m, 2.50 m and 3.02 m. Instead of using a fiber grating array continuously tunable FSR can be obtained by using a fiber chirped grating [5]. To

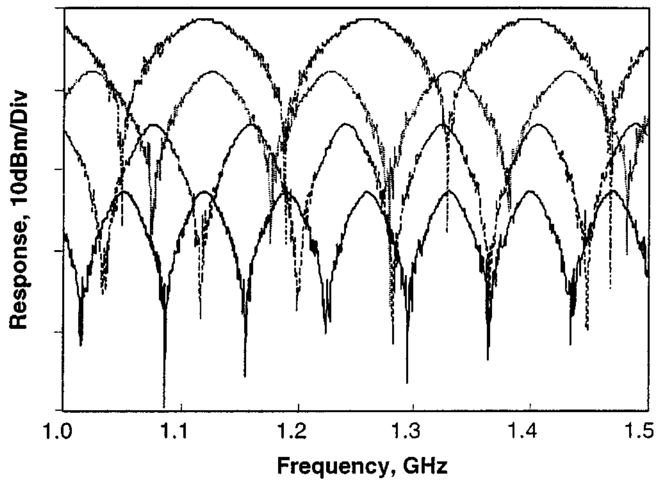


Fig. 4. Measured frequency responses with tunable FSR. For the traces from top to bottom the operating wavelength set at 1543.6 nm, 1548.1 nm, 1552.7 nm, and 1556.9 nm.

achieve large tuning of the FSR, however, a very long chirped grating has to be used.

IV. Conclusion

In conclusion, we have demonstrated the achievement of both the maximum notch depth and tunable free spectral range in an optical fiber recirculating delay line. The effect of insertion loss on the performance of optical fiber recirculating delay line has been fully investigated, and used to obtain the maximum notch depth. The tunable free spectral range has been realized by incorporating a fiber Bragg grating array. It would potentially allow reconfiguration of the filter at nanosecond speeds, corresponding to the electronic tuning speeds of lasers [7]. It should be pointed out that any insertion loss not in the fiber loop does not have the above effect, except reduce the transmitted optical power through the delay line. Inducing insertion loss can maximize the notch depth of optical fiber recirculating delay line with coupling coefficient less than 1/3. If both insertion loss and gain (using optical amplifier, for instance) are induced, maximized notch depth for almost all the coupling coefficients can be achieved. Introduction of gain into recirculating delay line can also generate bandpass response with high quality factor. Finally any insertion loss is not wanted in practical application, however it can now be compensated by use of Erbium-doped optical fiber amplifier.

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