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A Novel Digitally Tunable Microwave-Photonic Notch Filter Using Differential Group-Delay Module

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***Abstract*—We demonstrate a digitally tunable microwave-photonic notch filter based on a differential group-delay module which produces a relative delay between two orthogonal polarizations. A maximum rejection level greater than 60 dB is obtained. The tunability of the filter is achieved through real-time electronic control of the relative delay time.**

***Index Terms*—Differential group delay (DGD), microwave photonics, notch filter.**

MICROWAVE photonics techniques have been broadly explored for microwave and millimeter wave communication and signal processing [1]. One particular application of interest is the transversal microwave notch filter which can be used for various wireless communication and radar applications. Many promising approaches to achieve the notch–bandpass filter based upon optical delay line concept have been proposed [2]–[5]. A common limitation of these incoherent transversal filters, namely, the high-frequency operation range, is caused by the optical coherence of the light source, which increases the coherence noise [6]–[8]. [6] removes this limitation by making use of the two orthogonal polarizations in hi-birefringence (Hi-Bi) fiber. It was noted that the time delay in Hi-Bi fiber can be tuned through temperature variation and its performance can be affected by the ambient temperature variation.

In this work, we demonstrate a novel tunable notch filter through an off-the-shelf fiber-optic programmable differential group-delay (DGD) module, DGD-6B1, made by General Photonics Corp. [9]. This filter serves two functions: it removes the limitation due to the coherence of the light source, and it allows digitally tunable notch-filtering operation.

As described in [9], the DGD module with dimensions of $134 \times 70 \times 20\text{mm}^3$ has six phase delay sections each of which consists of a birefringent crystal and a magneto-optic polarization switch. The lengths of the birefringent crystals are arranged in a binary power series, incremented by a factor of 2 for each section. The relative delay between two orthogonal linear polarization states can be digitally switched from -45.2 to $+45.2$ ps with a resolution of 1.36 ps, i.e., 6-bit resolution. The average DGD switching speed is 150 μs. The optical insertion loss is 2.4 dB.

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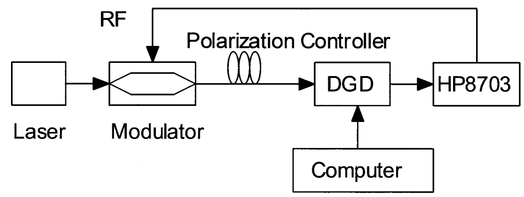

Fig. 1. Experiment setup of the tunable notch filter using the DGD module.

The operation of the module is computer controlled using the software provided by the manufacturer. Due to the small size and the programmability of DGD, the filter is quite compact and robust in operation.

Fig. 1 depicts the experiment setup. The source is a single-mode Alcatel distributed feedback laser with a linewidth of 2–5 MHz. It has a relatively long coherence time. In the test setup, the continuous-wave output of laser is modulated by a Mach–Zehnder $LiNbO_3$ modulator with a 3-dB bandwidth of 10 GHz. The polarization controller adjusts the input polarization to the DGD module, i.e., at an azimuth of 45° to the polarization axis of DGD, so that the two orthogonal polarization states can be equally excited.

The operation of this notch filter is described as follows. The six sections of the DGD module are separately biased to give a relative delay time τ between the two orthogonal polarizations. When the modulated optical input is properly polarized with respect to the module, the optical output consists of two orthogonal polarizations with a relative delay time τ between them. The normalized output power spectrum $\mathrm{P_N}(\Omega)$ at the detector takes the form of

$$P_N(\Omega) = \cos^2 \pi\Omega\tau \tag{1}$$

where Ω is the modulating microwave frequency. Thus, the notches occur when

$$\Omega\tau = n + \frac{1}{2} \tag{2}$$

where n is an integer number.

Fig. 2 depicts the simulated normalized power spectrum of the notch filter after the detector, when the delay time is set at 45.2 ps. In principle, the rejection level of this filter could reach infinity when the two orthogonal states are equally excited. In practice, due to the unequal optical loss, unbalanced excitation

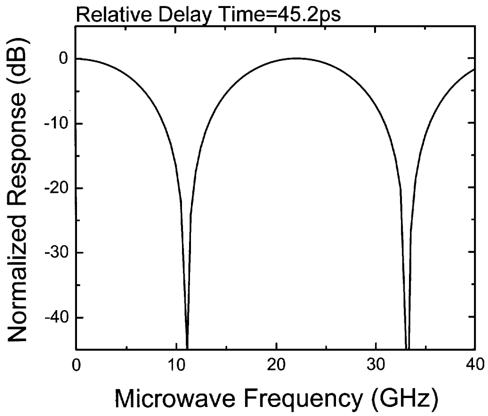

Fig. 2. Simulated frequency response of the notch filter at delay time 45.2 ps.

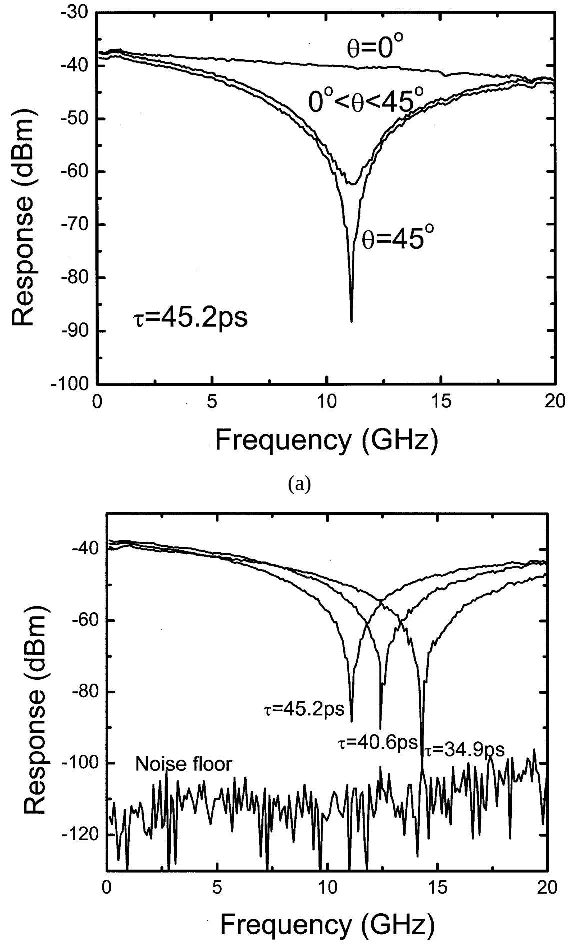

Fig. 3. (a) Detected output as a function of frequency when input polarization azimuth adjusted. (b) Notch frequency is tuned by adjusting delay time.

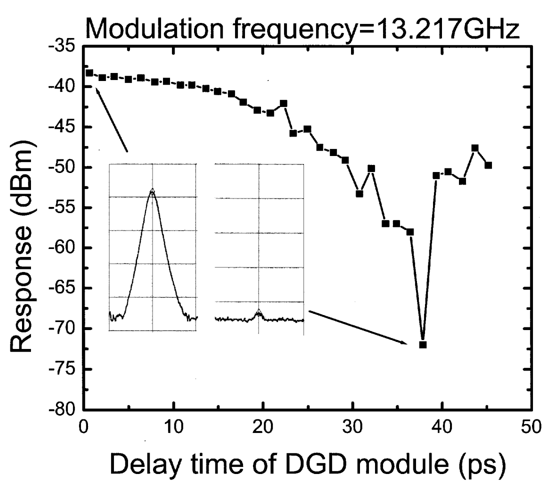

Fig. 4. Output response at the spectrum analyzer as a function of the delay time, the modulation frequency is fixed at 13.2 GHz. The spectrum analyzer is set at a resolution bandwidth of 100 kHz and span of 5 MHz, and has a noise floor of around -77.0 dBm.

of the two states, and the noise floor of the system, the observed rejection level remains finite in value.

The minimum and maximum relative delays of the present DGD module are 0.68 and 45.2 ps, respectively, corresponding to the first notch frequency $(\mathrm{n} = 0)$ at 735 and 11.06 GHz, respectively. In the vicinity of 11 GHz, where the filter was tested, the tuning step is about 0.33 GHz which is limited by the bit resolution of the DGD module. To ensure the DGD is thermally stable, the data are taken after the setup is warmed up for one hour.

Fig. 3(a) shows the measurement results when the delay time is set at 45.2 ps. When linearly polarized light is launched along one of the polarization axes of the DGD module, i.e., $\theta = 0°$, no filter function is expected. This is similar to the observation in [6] using the Hi-Bi fiber delay line. However, using an input linearly polarized at an azimuth of 45° to the two polarization axis, two orthogonal modes are excited with a relative delay of 45.2 ps, and the notch frequency at 11.06 GHz is observed with a maximum rejection level greater than 50-dB rejection. Fig. 3(b) shows that when the delay time is tuned from 45.2 to 40.6 and 34.9 ps, the notch moves to 12.3 and 14.3 GHz, respectively. The highest rejection level reached is $>$ 60 dB, and is limited by the noise floor of the measurement system. A rejection level of 50 dB can be stably obtained.

Next, we examine the filter function at a fixed modulation frequency at the input as the delay time is scanned. The input modulation frequency is set at 13.2 GHz and then the delay time of the DGD module is swift from 0.68 to 45.2 ps. In the measurement setup, the fixed modulation frequency is generated by an radio frequency synthesizer HP83620A while the output is detected by an external high speed detector followed by a microwave spectrum analyzer HP70000. The first notch for this input occurs when τ is around 37.8 ps, as shown in Fig. 4, which is consistent with the prediction of (1). The two insets in Fig. 4 show the spectra at delay time of 0.68 ps (left) and 37.8 ps (right), respectively.

As an extension of this approach, more complex filter response such as bandpass filter, could be achieved by using multiple DGD modules in parallel arrangement, with different delay, and detected with a photodiode array. This is similar to the approach used in [10], except due attention on experimental conditions such as absolute delay time compensation will be needed.

In summary, we have successfully demonstrated a novel digitally tunable notch filter using a programmable time-delay module. The tuning resolution and range are presently limited by the bit resolution of the DGD module. A maximum rejection level greater than 60 dB was observed.

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