

Tunable microwave photonic notch filter with two Hi-Bi couplers

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We demonstrate a tunable microwave-photonic notch filter based on two 3dB Hi-Bi couplers, a half-wave plate, and a variable time delay line. The configuration is free from the problems of optically coherent interference and chromatic dispersion. Expressions for the filter transfer function, as well as its application in a 20 km radio-over-fiber (RoF) link, are presented. Measured results match the calculated results and show a notch rejection greater than 35 dB. The scheme can operate over a wide range of optical carrier frequencies.

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1. Introduction

All-optical processing of microwave and millimeter-wave signals provides advantages such as large time-bandwidth products, insensitivity to electromagnetic interference and lightweight. A very useful component in radio frequency (RF) systems is a high-resolution tunable notch filter. A number of photonic microwave filters have been reported in the literature [1]-[5]. In this application, it is required to achieve optically incoherent summing of two light signals. To overcome the optical coherence problem, either a laser array is used [1], or the coherence time of the light source is kept smaller than the minimum delay time of the filter [2, p. 5]. Incoherent summing has also been achieved by using a Hi-Bi fiber [3]; however, such a filter cannot be tuned easily and needs a long Hi-Bi fiber for small free spectral range (FSR) values. A step tunable design with a tunable laser and uniform Hi-Bi gratings is reported in [4]. A continuously tunable design using a Hi-Bi chirped grating has been reported in [5]; unfortunately, the grating causes a very large chromatic dispersion, which will affect the system performance; the operating wavelength range is also limited due to the FBG bandwidth; moreover, phase noise will be introduced by the crosstalk when the chirped grating is tuned. Finally, the design in [5] can not operate in a Radio-over-fiber (RoF) link, due to the different sign of chromatic dispersion for the two orthogonal states of polarization.

In this paper, we demonstrate a tunable microwave-photonic filter based on two 3-dB Hi-Bi couplers, a variable time delay line and a half-wave plate. The configuration is free from the problems of optical coherent interference. Expressions for the filter transfer function are derived and measured results are presented to demonstrate the filter operation. Application in a 20 km SMF RoF link is also analysed theoretically and demonstrated experimentally. A notch rejection greater than 35 dB is obtained. It is shown that the notch frequency is continuously tunable by tuning the time delay line. The scheme can operate over a wide range of optical carrier

frequencies, restricted only by the bandwidth of the various optical components in the system.

2. System configuration and operating principle

The filter configuration is shown in Fig. 1. An RF signal drives an electro-optic intensity modulator (EOM), which modulates the output of a 1550 nm ANDO (AQ8201-13A) laser with 5MHz linewidth. The output of the EOM, which has a Hi-Bi pigtail, is launched into the first 3 dB Hi-Bi coupler, which also has Hi-Bi Pigtails. One of the output arms of the first 3 dB Hi-Bi coupler incorporates a time delay line with a Hi-Bi pigtail and is connected to the second 3 dB Hi-Bi coupler through a fiber of length L_1 . The time delay line can provide a tunable time delay, from 0 – 330 ps, with a 1 ps resolution, between the two arms interconnecting the two 3 dB Hi-Bi couplers. A half-wave plate is inserted in the other output arm of the first Hi-Bi coupler; this enables one to change the state of polarization (SOP) of arm 2 that has a polarization orthogonal to that in arm 1. The time delay line (OZ Optics Ltd.) has an insertion loss of about 2.5 dB. The half-wave plate is inserted in a fiber bench with an insertion loss also of about 2.5 dB. This ensures that equal optical power is incident on the input ports of the second coupler; this leads to a strong notch in the filter response. The second Hi-Bi coupler combines the two input signals that are orthogonally polarised. One output port of the Hi-Bi coupler is connected to a photo-detector and a vector network analyser. The other output port of the Hi-Bi coupler is connected to a 20 km SMF RoF link. The differential time delay between the two branches of the resulting filter consists of two parts: one caused by the length difference between L_1 and L_2 and the other caused by the time delay $\Delta\tau_d$ provided by the time delay line.

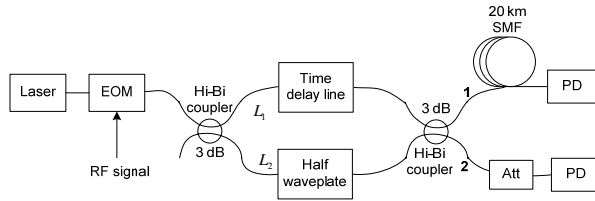


Fig. 1. Experimental setup.

When α is $\pi/2$ for the half-wave plate, then the SOP for arm 2 is orthogonal to arm 1, leading to a maximum notch depth in the filter response [3]. Let the input RF voltage to the external modulator be represented as

$$V(t) = 1 + m \cos \omega_m t \quad (1)$$

Considering a linear intensity modulation, the output optical power of the modulator can be expressed as:

$$P_i(t) = P_i(1 + m \cos \omega_m t) \quad (2)$$

where P_i is the optical power output from the laser, m is the modulation index, which equals the peak intensity change divided by the average intensity [6], and ω_m is the modulating angular frequency. The corresponding electric field of the light wave can be expressed as:

$$f(t) = \sqrt{P_i} \sqrt{1 + m \cos(\omega_m t)} \cos(\omega_0 t) \quad (3)$$

where ω_0 is the angular frequency of the optical carrier signal. It is assumed that the modulator has a Hi-Bi pigtail and the polarization of the output light from the laser is optimally aligned to the modulator. Under small signal condition ($m < 1$), Eq. (3) can be approximated as:

$$\begin{aligned} f(t) &= \sqrt{P_i} \left(1 + \frac{1}{2} m \cos \omega_m t \right) \cos \omega_0 t \\ &= \sqrt{P_i} \left[\cos \omega_0 t + \frac{m}{4} \cos(\omega_0 + \omega_m) t + \frac{m}{4} \cos(\omega_0 - \omega_m) t \right] \end{aligned} \quad (4)$$

The Fourier transform of the signal is written as:

$$F(\omega - \omega_0) = \int_{-\infty}^{+\infty} f(t) \exp[-j(\omega - \omega_0)t] dt \quad (5)$$

To begin with, we ignore the fiber link in output arm 1 of the second Hi-Bi coupler. Assuming equal power in the two arms interconnecting the couplers, the signals in the two output arms of the second coupler can be expressed as:

$$f_{\Omega+}(t) = M \sqrt{P_i} \left\{ \begin{aligned} &\cos(\omega_0 t) + \frac{m}{4} \cos[\omega_0 t + \omega_m(t - \beta_1 L_1 - \Delta \tau_d)] \\ &+ \frac{m}{4} \cos[\omega_0 t - \omega_m(t + \beta_1 L_1 + \Delta \tau_d)] \end{aligned} \right\} \quad (6)$$

$$f_{\Omega-}(t) = M \sqrt{P_i} \left\{ \begin{aligned} &\cos(\omega_0 t) + \frac{m}{4} \cos[\omega_0 t + \omega_m(t - \beta_1 L_2)] \\ &+ \frac{m}{4} \cos[\omega_0 t - \omega_m(t + \beta_1 L_2)] \end{aligned} \right\} \quad (7)$$

where $\Delta \tau_d$ is the time delay introduced by the time delay

line and $\beta_1 = \left. \frac{d\beta}{d\omega} \right|_{\omega=\omega_0}$ and M is an amplitude factor.

Since the two signals are orthogonally polarized, the optical signal power at the detector is

$$P(t) = |\vec{f}(t)|^2 = \vec{f}(t) \cdot \vec{f}^*(t) = |f_{\Omega+}(t)|^2 + |f_{\Omega-}(t)|^2 \quad (8)$$

Eq. (8) shows that the optical power incident on the photodetector consists of two components with orthogonal states of polarization, thus getting rid of the coherence problem induced by the laser source. By assuming the responsivity of the photodiode to be R , we get the RF output current as:

$$\begin{aligned} I(t) &= RM^2 P_i \cdot \left\{ \begin{aligned} &\frac{1}{2} + \frac{m}{2} \cos[\omega_m(t - \beta_1 L_1 - \Delta \tau_d)] \\ &+ \frac{m^2}{8} [\cos(\omega_m(t - \beta_1 L_1 - \Delta \tau_d))]^2 \end{aligned} \right\} \\ &+ RM^2 P_i \cdot \left\{ \begin{aligned} &\frac{1}{2} + \frac{m}{2} \cos[\omega_m(t - \beta_1 L_2)] \\ &+ \frac{m^2}{8} [\cos(\omega_m(t - \beta_1 L_2))]^2 \end{aligned} \right\} \end{aligned} \quad (9)$$

Under small signal conditions, the m^2 terms in Eq. (9) can be neglected. Next, comparing the RF output current in Eq. (9) with the RF input voltage in Eq. (1) one gets the transfer function of the microwave filter:

$$|H(\omega_m)| = RM^2 \left| \exp[-j(\beta_1 L_1 + \Delta \tau_d)\omega_m] + \exp[-j(\beta_1 L_2)\omega_m] \right| \quad (10)$$

When the output arm 1 of the second coupler is connected to a 20 km SMF RoF link, the signals in the two orthogonal states of polarization can be expressed as:

$$f_{\Omega+}(t) = M \sqrt{P_i} \left\{ \begin{aligned} &\cos(\omega_0 t) + \frac{m}{4} \cos[\omega_0 t + \omega_m(t - \beta_1 L_1 - \Delta \tau_d) - \beta_2 l \omega_m^2 / 2] \\ &+ \frac{m}{4} \cos[\omega_0 t - \omega_m(t + \beta_1 L_1 + \Delta \tau_d) - \beta_2 l \omega_m^2 / 2] \end{aligned} \right\} \quad (11)$$

$$f_{\Omega-}(t) = M \sqrt{P_i} \left\{ \begin{aligned} &\cos(\omega_0 t) + \frac{m}{4} \cos[\omega_0 t + \omega_m(t - \beta_1 L_2) - \beta_2 l \omega_m^2 / 2] \\ &+ \frac{m}{4} \cos[\omega_0 t - \omega_m(t + \beta_1 L_2) - \beta_2 l \omega_m^2 / 2] \end{aligned} \right\} \quad (12)$$

where l is the length of the SMF RoF link and

$\beta_2 = \left. \frac{d^2\beta}{d\omega^2} \right|_{\omega=\omega_0}$. Similar to the analysis for Eq. (8)

and Eq. (9), and using the dispersion parameter

$D = -2\pi c\beta_2/\lambda^2$, the transfer function of the microwave filter in this case is

$$|H_{RF}(\omega_m)| = RM^2 \cos(\omega_m^2 \lambda^2 D l / 4\pi c) \exp[-j(\beta_1 L_1 + \Delta\tau_d)\omega_m] + \exp[-j(\beta_1 L_2)\omega_m] \quad (13)$$

The time delay between the two taps of filter is

$$\Delta\tau = \Delta\tau_0 + \Delta\tau_d \quad (14)$$

where $\Delta\tau_0 = \beta_1 L_1 - \beta_1 L_2$ is the fixed time delay. The notch frequencies are given by:

$$f = \left(k + \frac{1}{2}\right) \frac{1}{\Delta\tau}, \quad k = 0, 1, 2, \dots \quad (15)$$

When one changes the value of time delay $\Delta\tau_d$, the FSR varies according to Eq. (15).

3. Experimental results

First, the difference between L_1 and L_2 is about 0.1058 m and $\Delta\tau_d$ is zero. So the fixed time delay value $\beta_1 L_1 - \beta_1 L_2$ is about -528.8 ps. As shown in Fig. 2 (a), a filter with an FSR of 1.891 GHz and notch depths more than 35 dB is obtained. Fig. 2 (b) includes the measured result when $\Delta\tau_d$ is about 211 ps, corresponding to an FSR of about 3.148 GHz. Small fluctuations in the magnitude response at higher frequencies are due to the fluctuation of responsivity of the photodiode (R). Otherwise the filter operation is very stable, which means that the operation is free from the problem of optical coherence. One of the advantages for the design shown in Fig. 1 is that it can easily give much smaller FSR values using relatively short fiber lengths. In comparison, using a design based on Hi-Bi fiber [3], in one of the experiments performed by us, a 490 m long Panda Hi-Bi fiber is needed for achieving an FSR of 1.536 GHz.

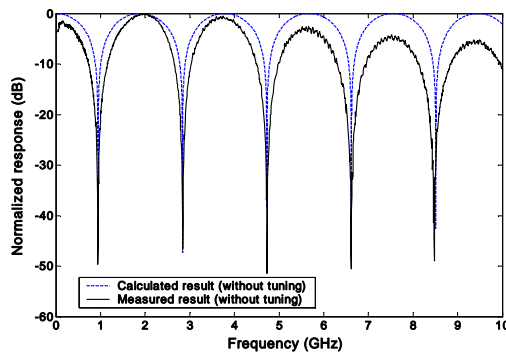


Fig. 2. (a) Measured and calculated notch filter response for $\Delta\tau_d = 0$.

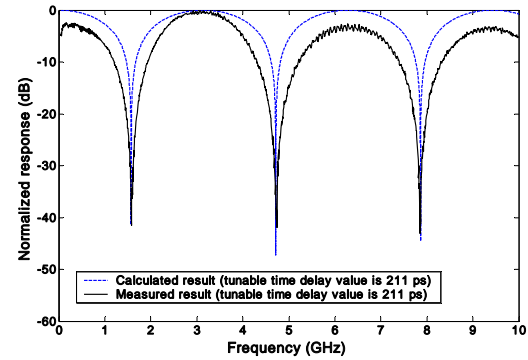


Fig. 2(b) Measured and calculated notch filter response for $\Delta\tau_d = 211$ ps.

The measured and calculated FSR values for different values of time delay are shown in Fig. 3. Our experiment results agree well with the calculated results. For the calculated results, the fixed time delay is -528.8 ps, and the equation used is $FSR = 10^3 / |-528.8 + x|$ (GHz), where x is the value of the tunable time delay ($\Delta\tau_d$). It is possible to use larger values of time delay by using a different time delay line. Also, a bandpass filter can be realized by using phase modulation with the help of a dual-drive modulator.

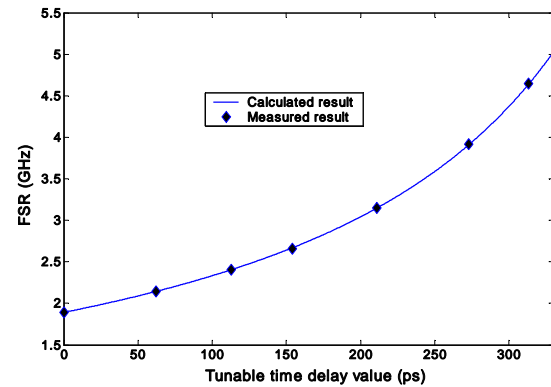


Fig. 3. Measured and calculated FSR with different values of $\Delta\tau_d$.

Fig. 4 shows the filter application in a 20 km single mode fiber link. Fig. 4(a) shows that with $\Delta\tau_d = 0$, the filter FSR is again 1.891 GHz and notch depths more than 30 dB are obtained. Fig. 4(b) shows the results for $\Delta\tau_d = 211$ ps, corresponding to an FSR which is the same as that in Fig. 2(b). The carrier suppression effect, due to the 20 km SMF, given by $\cos(\omega_m^2 \lambda^2 D l / 4\pi c)$, is included in the calculated results in Fig. 4. This effect reduces the response at higher frequencies. Further, the fluctuation in the filter response is more when the 20 km SMF is included.

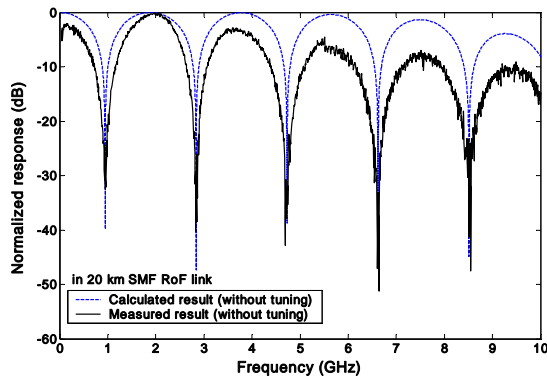


Fig. 4. (a) Measured notch filter response including a 20 km SMF RoF link with $\Delta\tau_d = 0$

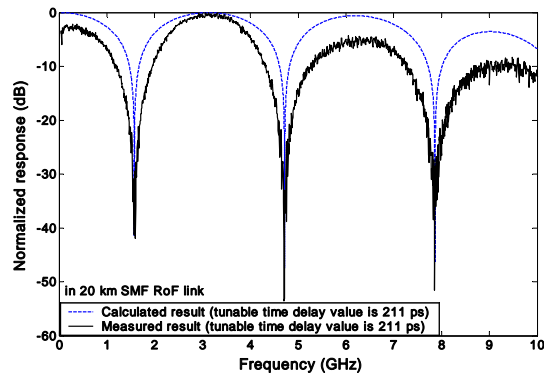


Fig. 4. (b) Measured notch filter response including a 20 km SMF RoF link with $\Delta\tau_d = 211$ ps.

4. Conclusion

We have demonstrated a tunable microwave-photonic filter based on two Hi-Bi couplers, a variable time delay line and a half-wave plate. The configuration is free from the problems of optically coherent interference. Measured results show a notch rejection greater than 35 dB; also, the notch frequency is continuously tunable by adjusting the time delay line. The filter application in a 20 km SMF RoF link has also been demonstrated. The filter transfer function has been derived for the different cases. By using a time delay line with a larger tuning range of time delay values, the tuning range of the notch frequency can be extended further. The scheme can yield small FSR values without needing long Hi-Bi fiber lengths and can operate over a wide range of optical carrier frequencies. The measured results agree well with the calculated results.

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