Tunable Optical Filters Using Compound Ring Resonators for DWDM

Carmen Vázquez, Salvador Vargas, José Manuel S. Pena, and Pedro Corredera

Abstract—**The device is based on a loop mirror in a ring resonator. The loop mirror allows tuning by changing the coupling coefficient of a directional coupler. The loop mirror is implemented using a Sagnac configuration to have the same optical path between the signals to be interfered (copropagating and counterpropagating ones). The filter structure allows optical integration for having higher free-spectral ranges. Simple design equations for the filter parameters and the tuning are reported. Measurements on a passive optical fiber tunable filter are presented. There is a good agreement between measurements and theory.**

***Index Terms*—Optical delay lines, optical filters, optical transfer functions, tuning and optical couplers.**

I. Introduction

THE NEED for increasing bandwidth has driven standards institutions to extend the transmission windows from the conventional C-band to O-, E-, L-, S-, U-bands and/or to reduce the channel spacing. This last technique is used in the dense wavelength-division-multiplexing (DWDM) systems with carriers spacing of 50 GHz or less [1]. This denser spectrum needs filters able to separate very narrow channels with low crosstalk levels. Another interesting approach is to have filter structures easily translated to an integrated optic implementation with a high level of integration [2], [3]. On the other hand, the utilization of subcarrier multiplexed (SCM) data channels in DWDM optical networks has many potential important roles including packet addressing, performance monitoring using subcarriers, and network management and control. These systems require an efficient method to monitor, extract and potentially erase subcarrier information. In this respect, optical filtering techniques have been used to simplify SCM receiver designs [4]. These filters must have high rejection ratios and free-spectral ranges (FSRs) of tenths of gigahertz.

According to the previous requirements, different optical filters have been developed [5], [6] using as building blocks Mach–Zehnder (MZ) interferometers and recirculating delay lines with phase shifters, amplified ring resonators, and loop mirrors [2]–[4], [7]. Even compound ring resonators are reported [8] but in a slightly different configuration, and there is no use of the coupling coefficient as the tuning parameter nor a mention about it. In this letter, we present a tunable filter, based on the structure reported in [9], a ring resonator with a Sagnac configuration as a loop mirror in it, but operating as a notch filter, so using its passive form. It is an easy configuration to implement in optical fiber technology and it can also be integrated in InP or silicon technology. The Sagnac configuration allows us to have the same optical path between the counter and copropagating signals in comparison with other configurations based on Michelson devices [10]. The transfer matrix formalism is used for deriving the design equations. The results show the tunability of the device for a certain set of values of the design parameters. Measurements on a fiber-optic prototype validate the theoretical model, the design equations, and the tuneability.

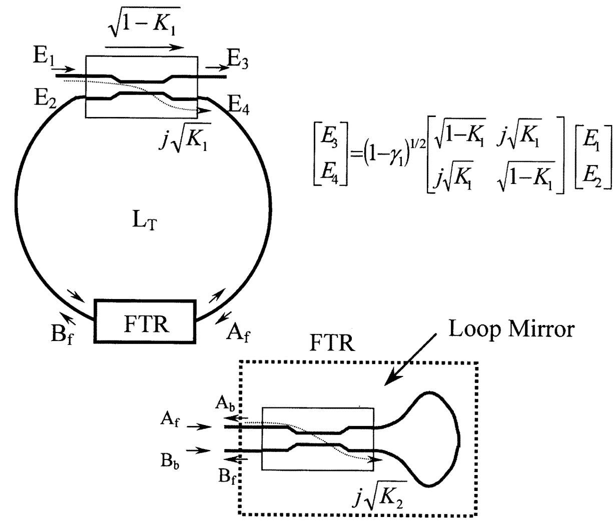

Fig. 1. Schematic of the device.

II. Filter Architecture and Design

Passive optical filter architecture is shown in Fig. 1. It is made of a multireflection function (FTR) in a ring resonator. The multireflection function is implemented using a loop mirror that allows for tuning the device using the coupling ratio K_2.

Filter design equations are derived using the transfer matrix formalism and the unfolded equivalent model, as in [8]. Doing so, the normalized output power is obtained, as shown in (1)–(6), at the bottom of the next page, where E_3 is the output field at Port 3 and E_1 the input field at Port 1, γ_1, K_1, and γ_2, K_2 are the excess loss and the power coupling coefficient of the input coupler and of the loop mirror coupler, respectively (see Fig. 1). So the through- and cross-port transmission for the input coupler are $\tau = \sqrt{1-K_1}$, $j\kappa = j\sqrt{K_1}$. L_T is the total length

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including the ring and the Sagnac loop length, α is the attenuation coefficient and β is the propagation constant in the total fiber–waveguide.

The output power is zero at those frequencies that make the phases $\phi_{T1,2}$ in (1) an integer multiple of 2π and simultaneously $A_o/C/ = 1$. From (4), we obtain that those frequencies are given by

$$f_{1,2} = f_0 \pm \frac{c\phi_s}{2\pi n_{\rm nef} L_T} \quad f_o = m\frac{c}{n_{\rm nef} L_T}, \qquad m = 1, 2, 3 \ldots \tag{7}$$

where c is the speed of light in vacuum, $n_{\rm nef}$ the effective refractive index of the fiber or waveguide, and ϕ_s the second term of (4), which is used as the tuning angle.

If (6) is fulfilled and $A_o/C/ = 1$ [see (2)], there are two minimum frequencies, given by (7), in each FSR which are symmetrically placed around f_o. Tunability is limited to one half of the FSR of the device.

We can see from (4) and (7) that we can use K_1 and K_2 to select the location of the frequency of the minima, that is, for tuning the filter response. We can see that if K_2 is close to 0.5, there is a broad range of K_1 values for tuning. This range is reduced if $K_2 \to 0$ or 1.

The compound resonator can have an active medium in the ring resonator to balance losses [2], [9]. Better rejection ratios can be obtained depending on the proximity to fulfil the condition $A_o/C/ = 1$ [see (2)].

III. Experimental Setup and Measurements

In order to show the utility and the behavior of the designed passive optical filter, we have measured the output power for different K_2 values. A filter using optical fiber technology is implemented because it is a simpler technological alternative for us. Although, to have a greater FSR, integrated optical filters could be developed. This integrated version can be implemented because all the components of the design can be developed using integrated optics. In the case of using InGaAsP–InP technology, compact devices can be developed using multimode interference couplers with fixed coupling coefficients and codirectional tunable couplers; even semiconductor optical amplifiers can be used to control the losses, as reported in previous ring resonators fabricated devices with FSR of 25 and 50 GHz [2]. In the following, we describe the experimental setup and the measurements we have taken.

A. Experimental Setup

The setup used in the measurements includes a tunable laser Photonetics Tunics Plus-L (1510–1610 nm) at 1550 nm, with a 150-KHz linewidth and a side-mode suppression ratio >45 dB is used. To avoid temperature and vibrations effects among others due to the coherence nature of the measurements, we have externally modulated the laser with a radio-frequency (RF) signal through an MZ electrooptic modulator from UTP that modulates up to 4 GHz. The RF signal comes from a network analyzer (HP8510B) which sweeps a frequency window of 66 MHz, with 201 measurement points equally spaced, at a center frequency of 1 GHz. The optical detection is carried out by an optical-to-electrical (OE) converter (Tektronics OE-502), which consists of a Ge APD and a 40-dB attenuator. From the OE output, the network analyzer measures the output power amplitude and phase. Splices are used instead of connectors to avoid additional resonator perturbations in the measurements.

B. Measurements

As previously mentioned, our objective is to verify the tunability of our optical filter. In doing so, fulfilling (6) and using (7) and (4), we see that K_2 modifies the minima frequency location once K_1 is fixed. So we measure the filter response for different K_2 values, as shown in Figs. 2–4. The filter is made using 2 $\times$ 2 monomode fiber couplers with 1 m of pigtail in

$$\left|\frac{E_3}{E_1}\right|^2 = \frac{\left(1 + {A_0}^2|C|^2\right)^2 \left(1 - 2\cos\phi_{T1}\frac{A_0|C|}{1+{A_0}^2|C|^2}\right)\left(1 - 2\cos\phi_{T2}\frac{A_0|C|}{1+{A_0}^2|C|^2}\right)}{\left(1 + {D_0}^2\right)^2 \left(1 - 2\cos\phi_{D1}\frac{D_0}{1+{D_0}^2}\right)\left(1 - 2\cos\phi_{D2}\frac{D_0}{1+{D_0}^2}\right)} \tag{1}$$

with

$$A_0|C| = \sqrt{(1-\gamma_1)}(1-\gamma_2)e^{-\alpha L_T} \tag{2}$$

$$D_0 = \sqrt{(1-\gamma_1)(1-K_1)}(1-\gamma_2)e^{-\alpha L_T} \tag{3}$$

$$\begin{aligned}\phi_{T1,2} &= -\beta L_T \pm \phi_s \\ &= -\beta L_T \pm \arg\left(\frac{\sqrt{{K_1}^2(1-2K_2)^2 - 16(1-K_1)(1-K_2)K_2}}{(2-K_1)(1-2K_2)}\right)\end{aligned} \tag{4}$$

$$\phi_{D1,2} = -\beta L_T \pm \arg\left(\frac{2\sqrt{(1-K_2)\,K_2}}{(1-2K_2)}\right) \tag{5}$$

$$K_1 < -8A + 4\sqrt{4A^2 + A}$$

and

$$A = \frac{K_2(1-K_2)}{(1-2K_2)^2} \tag{6}$$

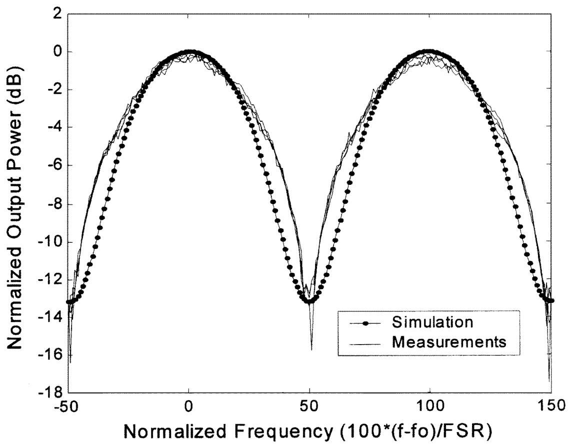

Fig. 2. Output power against frequency for $K_1 = 0.92, \gamma_1 = 0.075$, Loss $= 0.5, \gamma_2 = 0.075, \boldsymbol{K_2 = 0.75}$. Simulation $(\ldots)$. Measurements (__).

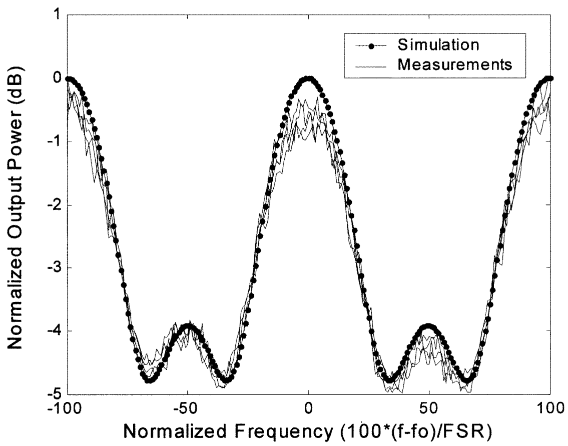

Fig. 3. Output power against frequency for $K_1 = 0.92, \gamma_1 = 0.075$, Loss $= 0.45, \gamma_2 = 0.075, \boldsymbol{K_2 = 0.60}$. Simulation $(\ldots)$. Measurements (__).

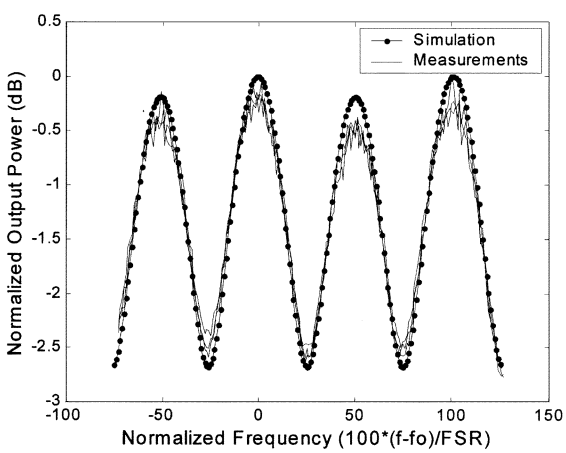

Fig. 4. Output power against frequency for $K_1 = 0.92, \gamma_1 = 0.075$, Loss $= 0.45, \gamma_2 = 0.075, \boldsymbol{K_2 = 0.505}$. Simulation $(\ldots)$. Measurements (__).

each port. Each measurement has been taken several times and the results of all of them are simultaneously plotted in Figs. 2–4, showing a good stability. By changing the K_2 value, different couplers have been used, so new splices have been developed in each measurement causing slightly different losses. The parameters of the measured filter are $K_1 = 0.92$, $\gamma_1 = 0.075$, $\gamma_2 = 0.075$, and Loss $= 0.5, 0.45,$ and 0.45 for Figs. 2–4, respectively. The *Loss* value includes the overall loss of the ring resonator and the Sagnac configuration due to propagation and splices to connect the different elements.

As expected, we can see how the minima are shifted in one FSR (33 MHz), with the shortest separation for $K_2 = 0.505$, increasing for $K_2 = 0.60$, and almost doubling for $K_2 = 0.75$. There is good agreement between measurements and theory. As we have not used any device to control the losses, the condition $A_o/C/ = 1$ [see (2)], is not completely fulfilled so the best measured crosstalk of 16 dB.

IV. Conclusion

A passive notch filter has been designed using a configuration with a compound resonator made of a Sagnac loop in a ring resonator. The multireflections originated by the loop are controlled through a coupling coefficient which is responsible of the tuning. Simple equations for designing and tuning are reported. A passive notch filter is implemented using fiber-optic technology. The structure can be developed using integrated-optics technologies. Measurements for different coupling coefficients are reported to verify the tuning characteristics of the device and to test the theory. Better crosstalk values on the measurements can be obtained through a proper control of the losses in the ring resonator.

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