Novel tunable optical filter employing a fiber loop mirror for synthesis applications in WDM

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Abstract: A novel optical filter employing a fiber loop mirror within an amplified ring resonator is presented. The fiber loop mirror allows tuning by changing the coupling factor of a coupler. The device can be used as a building block to synthesize optical filters, as previously reported, saving components.

Introduction

In recent years the increasing in the demand of capacity in fiber optic systems, has led to a rapid development of technology needed to satisfy this requirement. Many techniques to improve the performance of the fiber optic bandwidth have been implemented such as WDM (Wavelength Division Multiplexing), OFDM (Optical Frequency Division Multiplexing), within the C band (conventional band), among others. Nevertheless, the most successful techniques implemented to overcome this restriction are based on the increasing of the transmission window to near L and S bands (long and short wavelength bands) and the reduction in the spacing between carriers (less than 100 GHz). The last technique is named DWDM (Dense Wavelength Division Multiplexing) which has increased the transmission bandwidth of each channel from 2.5 Gb/s to 40 Gb/s [1], with carriers spacing of 50 GHz, making more efficient the transmission spectrum of fiber optics communications. These more dense spectra impose better filters to correctly separate adjacent channels with reasonable crosstalk levels.

Many synthesis methods for optical filters have been developed to achieve this objective [2-5]. These methods use as building blocks, Mach Zender (MZ) interferometers and recirculating delay lines, with phase shifters. In this paper, we present a new structure that substantially improves one of these methods, diminishing the number of couplers and phase shifters needed to perform the required filter characteristics.

Transfer Function

The figure #1 shows the structure of our device. It is formed by a Ring Resonator (RR) with a fiber loop mirror (FLM) in the middle of the ring, an optical amplifier (OA) and an outside coupler. The FLM introduces reflections, and has the next transfer functions:

$$FT = (1 - \gamma_2)(1 - 2K_2)e^{-(\alpha + j\beta)Lm} \quad (1)$$

$$FR = 2j(1 - \gamma_2)(K_2(1 - K_2))e^{-(\alpha + j\beta)Lm} \quad (2)$$

Where FT and FR are the transmission and reflection transfer functions, K_2 and γ_2 are the loss and coupling coefficient of the coupler, Lm is the fiber length in the FLM, α is the attenuation coefficient and β the propagation constant. The transfer function of this device can be obtained by means of the Z transform techniques [5] or with the transfer matrix formalism [6]. Applying the Z transform techniques we find the output transfer function in the ports P3, P4b and P4f, are given by:

$$\frac{P_3}{P_1} = (1 - \gamma_1)^{1/2} \left[\frac{((1 - K_1)^{1/2} - ((1 - \gamma_1)(1 - \gamma_3)G^*(1 - K_3))^{1/2})(2 - K_1)FT \cdot Z^{-1} + (1 - \gamma_1)(1 - \gamma_3)G^*(1 - K_3)(1 - K_1)^{1/2}(FT^2 - FR^2)Z^{-2}}{(1 - Z_{p1}Z^{-1})(1 - Z_{p2}Z^{-1})} \right] \quad (3)$$

$$\frac{P_{4b}}{P_1} = \frac{-((1 - \gamma_1)K_1K_3)^{1/2}(1 - \gamma_3)^{3/2}(1 - K_3)e^{(a + j\beta)Lx}FR \cdot Z^{-1}}{(1 - Z_{p1}Z^{-1})(1 - Z_{p2}Z^{-1})} \quad (4)$$

$$\frac{P_{4f}}{P_1} = \frac{-((1 - \gamma_1)(1 - \gamma_3)K_1K_3)^{1/2} [1 - (G^*(1 - \gamma_1)(1 - K_1)(1 - \gamma_3)(1 - K_3))^{1/2}FT \cdot Z^{-1}] e^{-(\alpha + j\beta)Lx}}{(1 - Z_{p1}Z^{-1})(1 - Z_{p2}Z^{-1})} \quad (5)$$

Figure #1: Schematic diagram of the device

Where: $\gamma_{1,3}$ and $K_{1,3}$ are the losses and coupling coefficients of the input and output couplers. $Z = e^{j\beta(Lx + Lm)}$, where Lx is the ring length. Lx is the length from the input coupler to the output coupler. $G^* = G \cdot e^{\alpha(Lx + Lm)}$ where G is the OA power gain. Z_{p1} and Z_{p2} are the poles of the transfer function, these poles are complex conjugated, with module and phase given by:

$$|Z_{p1,2}| = ((1 - \gamma_1)(1 - \gamma_3)(1 - K_1)(1 - K_3)G^*)^{1/2}(1 - \gamma_2) \quad (6)$$

$$\theta_{1,2} = \arctan \left(\frac{\pm 2(K_2(1 - K_2))^{1/2}}{1 - 2K_2} \right) \quad (7)$$

From (6) and (7), we obtain that the poles radial position can be controlled through of the G , and its phase through of K_2 . This means that the peaks maximum gain and the peaks position in frequency can be controlled by these two parameters (G and K_2). In figures #2 and #3, we see the transfer function of our device in P3 (3) and P4b (4) for different K_2 and the same gain, plotted vs. the normalized frequency given in radians (rad), where $2\pi \text{ rad} = 1 \text{ FSR}$. Where the FSR is the Free Spectral Range, which is given by:

$$FSR = \frac{c}{n(Lr + Lm)} \quad (8)$$

Where: n is the refractive index and c is the vacuum light velocity.

This device can be used as a tunable filter, where its tuning frequency is related to θ , by means of:

$$\Delta f = \frac{\theta}{2\pi} FSR \quad (9)$$

Where: θ is given in (7). As Example if we have a $FSR = 100 \text{ GHz}$, changing K_2 from 0 to

Figure 2: Transfer Function at Port P3, with $\gamma_1 = \gamma_2 = \gamma_3 = 0.05$, $G = 1.21$, $K_1 = K_3 = 0.1$, and $K_2 = 0, 0.3, 0.5$

0.4, the tuning of our device is $\Delta f = 21.8 \text{ GHz}$. We can tune from 0 radians to π radians, or the same from 0 to the half of FSR. One application of this tunable filter is to extract control channels modulated using sub-carrier multiple access (SCMA) modulation [7].

Figure #3 shows that the peak value of the transfer function for $K_2 = 0$ is near the double of the maximum peak for another K_2 . This is due to $K_2 = 0$, so we have a double pole for this gain, and it produces a greater maximum. In figure #2, this is not the case for the following reason: one of the poles is cancelled for one of the zeros of the function.

As we can see from (4) and figure #3, only the transfer function in port P4b is an all pole function, with complex conjugated poles. This all pole function can be used in the optical filters synthesis method described in [2]. This method uses all pole and all zero functions to synthesize Butterworth optical filters. With our device, we have two complex conjugated poles, tuning through a coupling coefficient. So no phase shifters are necessary to control the phase of the poles and we use one coupler less than the method reported every two stages.

Figure 3: Transfer Function at Port P4b, with $\gamma_1 = \gamma_2 = \gamma_3 = 0.05$, $G = 1.21$, $K_1 = K_3 = 0.1$, and $K_2 = 0, 0.3, 0.5$

Conclusions

A novel optical device employing an amplified ring resonator and a fiber loop mirror inside is presented and its transfer function is obtained. Simple expressions for the separation of the two maxima of this novel transfer function are derived. We have found that the maximum tuning range is the half of the Free Spectral Range. In addition, we have shown that one of the output ports of the transfer function can be used as building block for a optical filters synthesis method, as described elsewhere, saving components.

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