

# Flexible Tunable Spectrum Sliced Microwave Photonic Filter Using Parallel Fabry-Pérot Filters and Fiber Bragg Grating

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**Abstract**— A simple and low-cost spectrum sliced microwave photonic filter with high tunability has been implemented. This is based on use of two Fabry-Pérot filters with same free spectral range connected in parallel but one filter with an external fiber delay. An extension of this configuration with Fiber Bragg Grating (FBG) as delay element is also demonstrated. This architecture overcomes the tuning difficulties of a single Fabry-Pérot filter employed as a slicing element. Flexible tunability, large overall free spectral range and high quality factor have been obtained with the proposed configuration owing to the use of fiber delay/FBG. Wide and step tuning has been achieved in the frequency range of 41.1GHz to 50.23GHz in steps of 2.28GHz. The additional components are another Fabry-Pérot filter and fiber delay/FBG which makes the proposed architecture highly compact and cost-effective. Most of the practical difficulties faced in use of optical fiber are eliminated using FBGs. The characteristics of proposed configuration with different applied delays using fiber and FBG were tabulated. An analysis of flexible tunable property of the filter was made in terms of length of fiber delay and grating length of FBG and the results were plotted. Also quality factor calculation of the proposed filter was discussed.

**Index Terms**— Fabry-Pérot (FP) filter, Fiber Bragg Grating, fiber delay, Free Spectral Range (FSR), Microwave photonics, Q-factor, spectrum slicing, tunability.

## I. INTRODUCTION

Microwave photonics is today an innovative multidisciplinary and interdisciplinary field combining and transferring different technologies. Continued progress in photonic components and technology sustains great interest in this field and expanding acceptance of photonics for microwave systems. The many advantages of microwave fiber-optic communication links over conventional coaxial or waveguide links include reduced size, less weight, low cost and constant attenuation over the entire modulation frequency range. They have excellent reconfigurability, extremely wide bandwidth, low dispersion, high immunity to ElectroMagnetic Interference (EMI) and high information transfer

capacity. They are suitable for a number of applications such as personal communication networks, millimeter (mm)-wave radio LANs, antenna remoting, broadband video distribution networks and signal distribution for phased array antennas. With these new applications there are increasing requirements for high performance devices for microwave and mm-wave systems where they are used due to broadband low-loss and high-speed transmission capability of optical fibers. There is a great scope for developing 40GHz broadband cellular network technologies in the near term and there is an increased interest in the possibilities of using the 60GHz and 70GHz bands, with their excellent frequency reuse, for broadband pico-cellular operations. The breakthrough in the design and demonstration of several ultra broadband photonic components has paved the way for wideband and highly efficient optoelectronic converters used as important building blocks for microwave–optical links [1]. However, there is the difficulty of attaining the reconfigured band pass transfer function of any filter with the traditional microstrip or waveguide Radio Frequency (RF) technologies. This difficulty can be overcome by external on-line measures in spectrum sliced microwave photonic filters.

Several techniques have been deployed for spectrum slicing in microwave photonic filters [2] since 1996 up to 2008 and highly integrated and user-friendly software applications have also been developed [3] that enable the Computer-Aided Design (CAD) and simulation of these techniques. The fiber optic microwave and mm-wave filter demonstrated in the year 1996 is the first filter with highest number of filter taps, greater sidelobe suppression and fine, clear spectral slices [4]. A transmissive type FP filter with low spectral period was used to realize sub nanometer resolved optical sampling with the reported FSR of 4.6GHz.

Since an FP filter is a fixed optical filter, there are serious limitations of tunability and weight adjustment. The flexibility of this photonic microwave filter is very low and needs specially designed FP filter. It is difficult to achieve wide range of filter tunability since this requires the change of the slicing filter FSR. To tune the filter response, the Fabry-Pérot cavity has to be greatly changed to modify the FSR and the cavity has to be finely adjusted using optical switches and piezoelectrics [6]. This severely limits the practical feasibility of the architecture.

We propose an extension to the approach used in [4], [5] in order to obtain enhanced and wide-range tunability. This proposed architecture uses two FP filters in parallel but one of them with an adjustable fiber delay or FBG which gives flexible tunability in the range of 40GHz to 50GHz. Bragg gratings are attractive as sampling elements because the tap weights can be controlled via the grating reflectivity, the sampling time can be controlled via the grating spacing, and the interaction wavelength can be controlled via the grating pitch [7]. Second section explains the topology of the filter and analyzes the operation of the individual components. Section three discusses the simulated results obtained using the proposed architecture. Finally, we present the conclusions.

## II. FILTER TOPOLOGY AND OPERATION

The general layout of the filter is shown in Fig. 1. The optical source is a low-cost, broadband Amplified Spontaneous Emission (ASE) spectrum which is obtained from a pumped Erbium Doped Fiber Amplifier (EDFA). The ASE signal level however is usually very small and requires further amplification in order to overcome the losses introduced by the remaining components of the filter. The optical power from the source is split and spectrally sliced by use of two multiwavelength FP filters connected in parallel, one with an adjustable delay implemented using either optical fiber or FBG, to obtain the equivalent set of spectrally equispaced optical sources. The output light from the parallel combination FP filters is combined and subsequently modulated by RF signal by means of an external modulator and fed to an optical dispersive element providing a linear group delay characteristic. The output signal from the dispersive element is fed to a photodetector and subsequent RF circuit.

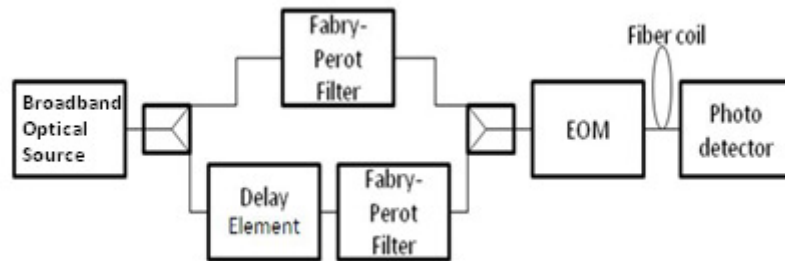


Fig.1. General Layout of the proposed configuration.

## III. THEORY

When Single-Sideband (SSB) modulation is employed for the RF signal and a single FP filter is used, the RF transfer function of the filter [5] is given as

$$|H_{RF}(\Omega)| = R \left| \sum_{k=1}^N P_k e^{-j [\Omega(k-1)\Delta\tau]} \right| \quad (1)$$

where  $P_k$  represents the output power from the  $k^{\text{th}}$  slice of the broadband source,  $R$  is the receiver responsivity,  $\Omega$  is the RF frequency, and  $\Delta\tau$  represents the incremental differential delay experienced by two adjacent spectral slices of the broadband source is given by

$$\Delta\tau = DL\Delta\lambda \quad (2)$$

where  $D$  (ps/km.nm) is dispersion parameter,  $L$  (m) is the length of fiber and  $\Delta\lambda$  (nm) is wavelength spacing. Equation (1) represents the spectral response of a Finite Impulse Response (FIR) filter where the number  $N$  of signal samples is equal to the number of significant spectral slices generated by the optical filter.

When two FP filters are used in parallel, the overall transfer function is given as

$$|H_{\text{overall}}(\Omega)| = |H_1(\Omega) + H_2(\Omega)| \tag{3}$$

$$= R \left| \sum_{k=1}^N P_k e^{-j[\Omega(k-1)(\Delta\tau_1)]} + \sum_{k=1}^N P_k e^{-j[\Omega(k-1)(\Delta\tau_2 + \tau)]} \right| \tag{4}$$

where  $\tau$  represents the time delay offered by the fiber or FBG.

When FBG is used as a delay element [8],

$$T_r = D_g L_g \Delta\lambda_t = 2 \bar{n} L_g / C \tag{5}$$

where  $T_r$  is the round-trip time for a grating of length  $L_g$ ,  $\Delta\lambda_t$  is the total shift in bragg wavelength,  $D_g$  is the dispersion parameter,  $\bar{n}$  is the average refractive index and  $c$  is velocity of light in the fiber.

#### IV. NUMERICAL RESULTS AND DISCUSSION

The MATLAB simulation platform was used to demonstrate the operation of the proposed microwave photonic filter shown in Fig. 2. To obtain sharply apodised sliced spectrum with  $N = 34$  taps, only a 9nm portion (centered at 1531.8nm, the wavelength corresponding to the ASE maximum of EDFA1) of the ASE output from EDFA1, was divided by means of a 1x2 splitter and fed to the FP filters connected in parallel. The output optical spectrum of broadband optical source was obtained using OPTSIM toolkit. The output from the FP filters was added using a 2x1 optical coupler. The optical dispersive element was implemented by means of a coil of 46km of singlemode standard optical fiber with dispersion parameter  $D = 17\text{ps/km.nm}$  and wavelength spacing of 0.28nm, although a linearly chirped fiber grating could also be employed. The output signal is amplified by EDFA2 and fed to a photodetector.

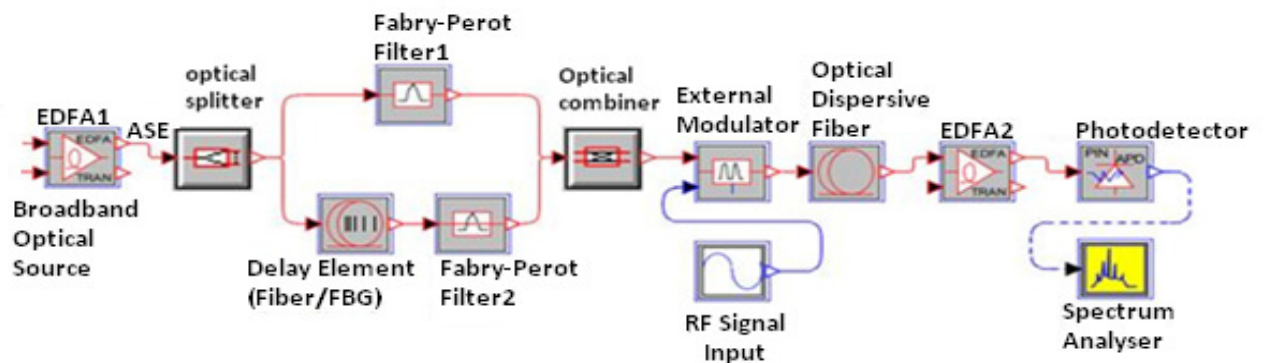


Fig.2. Proposed topology of the spectrum sliced microwave photonic filter.

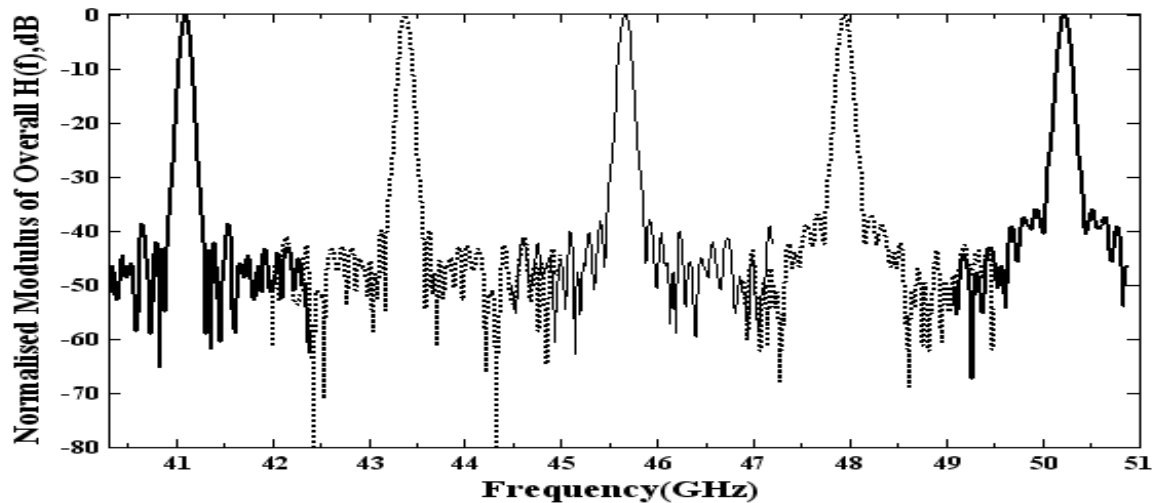


Fig. 3. Frequency characteristics of proposed configuration with the FP filter having same FSR with delay of 20, 42, 66, 92 and 122ps.

When two FP filters of same incremental differential delay  $\Delta\tau_1$  and  $\Delta\tau_2$  of 219ps were used in the configuration but without fiber delay, the response of the filter was not different from the response of a single filter as obtained in [4]. Then the two FP filters of same incremental differential delays  $\Delta\tau_1$  and  $\Delta\tau_2$  of 438ps ( $=17\text{ps/km.nm} \times 92\text{km} \times 0.28\text{nm}$ ) were used in the proposed configuration along with fiber delay. The fiber delay times  $\tau = 122\text{ps}$ ,  $92\text{ps}$ ,  $66\text{ps}$ ,  $42\text{ps}$  and  $20\text{ps}$  were offered by using singlemode standard fiber and adjusting its length to 25.6km, 19.3km, 13.9km, 8.8km and 4.2km respectively. This configuration provides high FSR and flexible tuning range from 40GHz to 50GHz. The FSR of this filter could be varied from 41.1GHz to 50.23GHz in steps of 2.28GHz. The filter frequency responses are shown in Fig. 3 obtained using (4) with the response of each configuration represented in a different trace, and other characteristics of this filter are mentioned in Table. I.

The delay times  $\tau = 122\text{ps}$ ,  $92\text{ps}$ ,  $66\text{ps}$ ,  $42\text{ps}$  and  $20\text{ps}$  were then offered by using FBG taking average refractive index  $\bar{n} = 1.447$  and  $c = 299792458$  m/s. Using (5) the grating length  $L_g$  was adjusted to 12.613mm, 9.559 mm, 6.811 mm, 4.324 mm and 2.064 mm and the results are given in Table. I. The same results as shown in Fig. 3. were obtained and are tabulated in Table. I. The required lengths of fiber delay were compared with required grating length. Thus FBGs of these grating lengths form effective substitutes for optical fiber as delay elements. There is no need to manually change the fiber length to obtain flexible tunability as in case of FBG is used as delay element. Also, the grating length required of FBG is very small in the order of millimeters compared to the length of fiber.

When no delay is given by fiber, the overall FSR is the frequency where a multiple of FSR of one filter is “sufficiently equal” to a multiple of FSR of the second filter. It is the first resonant frequency where the output powers of the filters sum up to give a total power of -3dB or more. Very high FSR is obtained when the FSR of the two filters differ very slightly (but usually with a delay time difference of around 10ps). The overall system loss of the architecture is compensated by the

use of EDFA2. From Table I. the required grating length is very small and is in the order of millimeter to obtain high FSR with step tunability.

TABLE I. COMPARISON TABLE OF CHARACTERISTICS OF PROPOSED CONFIGURATION WITH DIFFERENT APPLIED DELAYS USING FIBER AND FBG

S.No.	Fiber Delay $\tau$ (ps)	Required Length		Overall FSR (GHz)	3dB BW (MHz)	Quality Factor
		Fiber delay (km)	Grating $L_g$ (mm)			
1.	20	4.2	2.064	50.23	90	558
2.	42	8.8	4.324	47.94	100	480
3.	66	13.9	6.811	45.66	90	507
4.	92	19.3	9.559	43.38	90	482
5.	122	25.6	12.613	41.1	80	514

A. Q-Factor Calculation

The Q-factor of the overall filter is given as [9]

$$Q\text{-factor} = (\text{Overall FSR}) / (3\text{dB bandwidth}) \tag{6}$$

Fig.4 shows the offset response of the filter at 50.23GHz for the final tunable resonant peak. The overall FSR of 50.23GHz and a 3dB bandwidth of 90MHz ( $f_1 \sim f_2 = 50.18 \sim 50.27\text{GHz} = 90\text{MHz}$ ) were measured from Fig. 4. Using (6) the Q-factor of the filter at 50.23GHz was calculated and it is approximately of 558. In similar way, the Q-factor of the other resonant peaks were measured individually.

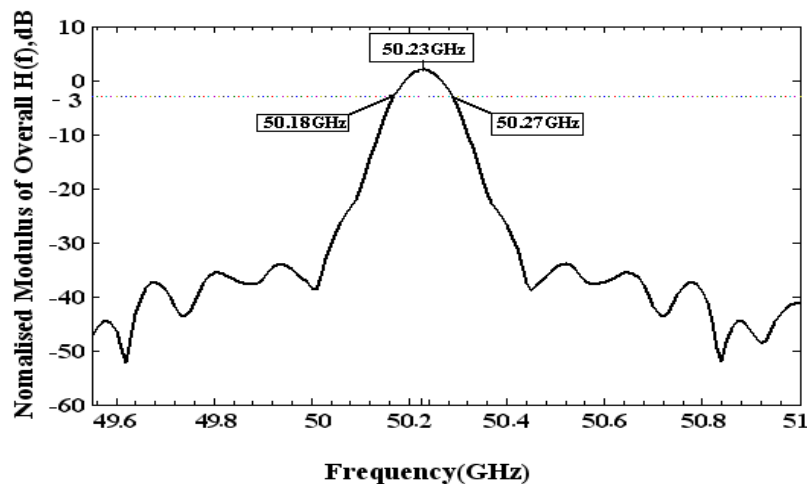


Fig. 4. Offset response of the filter at 50.23GHz.

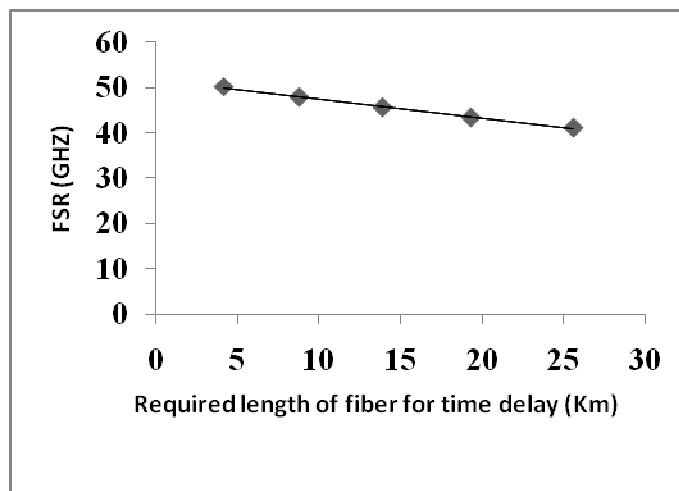


Fig. 5. FSR as a function of length of Fiber delay.

Fig.5 gives FSR as a function of length of fiber delay. The step tunability of the filter was achieved by adjusting length of fiber delay from 25.6km, 19.3km, 13.9km, 8.8km and 4.2km to vary the FSR from 41.1GHz to 50.23GHz in steps of 2.28GHz respectively. Fig. 6 gives FSR as a function of grating length. The same results as shown in Fig.3. were obtained using FBG with reduced grating length. The delay times  $\tau = 122\text{ps}$ ,  $92\text{ps}$ ,  $66\text{ps}$ ,  $42\text{ps}$  and  $20\text{ps}$  were offered by using FBG with the grating length  $L_g$  of 12.613mm, 9.559 mm, 6.811 mm, 4.324 mm and 2.064 mm respectively. Most of the practical difficulties faced in use of optical fiber are eliminated using FBGs. This makes the proposed architecture highly compact and cost-effective.

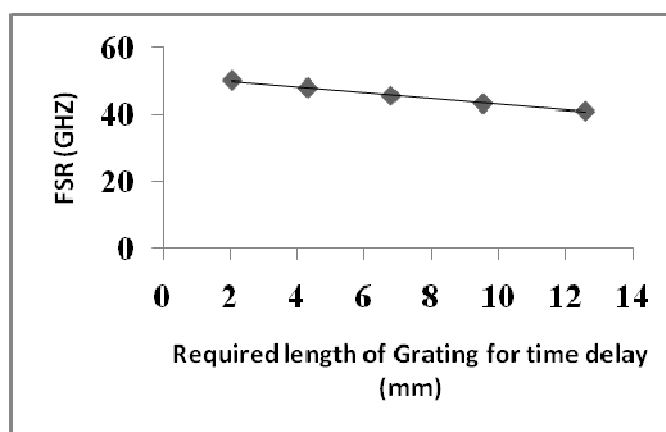


Fig. 6. FSR as a function of Grating length.

### V. CONCLUSION

We achieved flexible tunability for applications in the frequency range of 40 to 50GHz by employing two FP filters of same FSR of 2.28GHz (corresponding to differential incremental delay of

438ps) in parallel configuration, with one of them connected to variable optical fiber delay or FBG. This flexible tunability has been achieved by the use of the external delay element. The delay could be varied as  $\tau = 122, 92, 66, 42$  and  $20\text{ps}$  to vary FSR discretely from  $41.1\text{GHz}$  to  $50.23\text{GHz}$  in steps of  $2.28\text{GHz}$ . The results obtained are same for either optical fiber or FBG as delay element. Using FBGs, there is no need to manually change the fiber length to obtain flexible tunability. Also, the grating length required of FBG is very small compared to the length of fiber. The flexible tunable property of the filter was analyzed in terms of length of fiber delay and grating length of FBG and the results were plotted. The Q-factor of the proposed filter was measured. This makes the system compact and cost-effective.

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