Asian Journal of Information Technology 12 (6): 170-175, 2013
ISSN: 1682-3915

Reconfigurable Millimeter-Wave Photonic Filter Based on Spectrum Slicing by Cascaded Fabry-Perot Filters

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Abstract: Researchers propose and develop a simple and new reconfigurable millimeter-wave photonic transversal filter featuring high quality windowing property. The filter design is based on spectrum slicing of a broadband optical source by two cascaded fabry-perot filters. It shows the overall filter passband frequency response at millemeterwave band. This is obtained by properly choosing different free spectral range of two fabry-perot filters in cascaded configuration. The simulated results are presented to show that the overall filter free spectral range is 41.1 GHz. The 3 dB bandwidth is 50 MHz. It shows excellent side lobe suppression. A high quality factor of 822 has been reported. Reconfigurability of the filter is achieved by employing multiple apodization profile with two fabry-perot filters in cascaded form. The reconfigured frequency response of the filter is demonstrated for different windowing profiles and the results are tabulated. The results show high quality response of the filter. The advantage of this configuration is that a high performance filter is obtained without the need of any suppression of passband RF-spectral distortion which makes the system as simple and cost effective. It can be used for high density telecommunication networks and millemeterwave photonic communication systems.

Key words: Fabry-Perot filter, future generation network, millimeter-wave photonic filter, quality factor, reconfigurability, windowing

INTRODUCTION

Future broadband wireless access networks demand large bandwidth and fast data rate. Microwave/Millimeter-Wave Photonic Systems are playing an important role in future broadband wireless communication because of several advantages such as low loss, large bandwidth, reduced Electromagnetic Interference (EMI) among other typical advantages in optical systems (Hunter and Nguyen, 2006; Al-Raweshidy, 2010). The many advantages of microwave fiber-optic communication links over conventional co-axial 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 in ultrawide-band, multiple-access communications, personal communication networks, millimeter (mm) wave radio LANs, broadband video distribution networks and pulsed radar systems. 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 40 GHz broadband cellular network technologies in the near term. In these applications, a variety of RF signal-processing functions are necessary to facilitate interference rejection, signal conditioning, frequency selection and identification. The requirements on these filters include high selectivity or resolution, wide tunability and fast reconfigurability of the transfer function (Capmany *et al*., 2006). A microwave photonic filter satisfies these requirements by means of optical filtering of microwave/mm wave signals. In practical applications of microwave photonic filters such as radars, photonic beam steering of phased array antennas reconfiguration of the filter is an important and useful function (Gong *et al*., 2008). But it is very difficult to attain the reconfigured band pass transfer function of any filter

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with the traditional microstrip or waveguide RF technologies. This difficulty can be overcome by external on-line measures in spectrum sliced microwave/mm-wave photonic filters. Among various photonic microwave filter architectures, filters based on broadband optical spectrum slicing are simple and cost effective. Higher resolution, greater tunability and reconfigurability are achieved by this slicing method.

The various techniques for spectral slicing of broadband source such as interferometers, fiber Fabry-Perot (FP) filters, Fiber Bragg Gratings (FBG) were discussed (Sukanesh *et al*., 2008). A low cost tunable filter which is directly employable in optical domain was obtained by means of spectral sampling of LED source using fiber FP filters. But the tuning capability of this filter is very restricted (Pastor *et al*., 2003). Recently, Yi and Minasian (2008) demonstrated a novel multitap, flat top microwave photonic filter based on sinusoidal group delay gratings. It reported a high FSR of 7.8 GHz (Yi and Minasian, 2008). To overcome tuning capability of the filter and to obtain single band pass transfer function it has been proposed to use incoherent structures in cascade. The main idea is that by carefully choosing two filters, one with a lower Free Spectral Range (FSR) and selective resonances and a second with broader resonances and a higher FSR value in this cascaded configuration (Capmany *et al*., 2005). Thus, the overall filter transfer function is product of the transfer function of individual filter which yield high operating frequency. It has the combined features of the resonance selectivity of the first filter and broad FSR value of the second. A high Q-factor photonic microwave filter was implemented and demonstrated with two fabry-perot filters in cascaded form (Jeyachitra and Sukanesh, 2010b). It reported Q-factor of 959. The shape of the filter transfer function can be changed or reconfigured by the proper weighting or windowing of the time samples of its impulse response (Capmany *et al*., 1999a).

Researchers propose a new approach to obtain a simple, low cost reconfigurable mm-wave photonic filter operating in 40 GHz frequency band. Using two FP filters in cascaded form as a slicing element for a broadband source by choosing different FSR of individual filters which gives filter operating frequency in the range of 40-50 GHz. Reconfigurability of the filter was demonstrated by applying multiple windowing technique to the filter.

MATERIALS AND METHODS

Filter architecture: The general layout of the proposed filter configuration is shown in Fig. 1. The output light

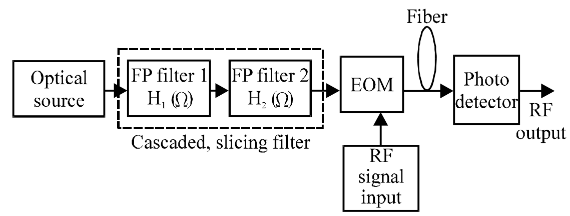

Fig. 1: General layout of the proposed configuration

emitted from the unmodulated broadband optical source is applied to cascaded filter configuration. The optical source is a low-cost, broadband ASE (Amplified Spontaneous Emission) spectrum (using LED or SLD) from a pumped Erbium Doped Fiber Amplifier (EDFA). However, the ASE signal level is usually very small and it requires further amplification in order to overcome the losses introduced by the remaining components of the filter. It consists of two FP filters of different FSRs one with smaller FSR and other with larger FSR value.

This configuration gives much finer and equally spectrally sampled signals. The output signal from cascaded combination is externally modulated by RF input signal. The modulated signal is fed to an optical dispersive fiber providing a linear group delay characteristic. The output signal from the dispersive element is fed to a photodetector and subsequent RF circuit.

Theoretical formulation: When SSB-RF modulation is employed, the transfer function of the filter is given by Capmany *et al*. (1999b) and Jeyachitra and Sukanesh (2010a):

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

Where:

P_k = The output power from the kth slice of the broadband source
R = The receiver responsivity
Ω = The RF frequency
$\Delta\tau = \beta_2\Delta\omega$ = The incremental differential delay experienced by two adjacent spectral slices of the broadband source
B_2 = The group delay slope of the dispersive element
Δω = Spectral spacing

Equation 1 represents the spectral response of a FIR filter where N is number of taps used in this filter. The number of taps gives the number of samples which are equal to the number of spectral slices generated by the optical filter.

The transfer function of first FP filter is $H_1(\Omega)$ and the second filter is $H_2(\Omega)$, respectively. Then, the overall filter transfer function of cascaded configuration is given by the product of the transfer function of individual filter (Jeyachitra and Sukanesh, 2010a, b) using Eq. 1:

$$|Hoverall(\Omega)| = |H_1(\Omega)H_2(\Omega)| = R\left|\sum_{m=1}^{N} P_m e^{-j[\Omega(m-1)\Delta\tau 1]} \sum_{n=1}^{N} P_n e^{-j[\Omega(n-1)\Delta\tau 2]}\right| \quad (2)$$

$$|Hoverall(\Omega)| = R\left|\sum_{m=1}^{N}\sum_{n=1}^{N} P_m P_n e^{-j\Omega[(m-1)(\Delta\tau 1)+(n-1)\Delta\tau 2)]}\right| \quad (3)$$

where, $\Delta\tau 1$ and $\Delta\tau 2$ are incremental differential delay of FP filter1 and FP filter2, respectively.

Design of reconfigurable filter: The shape of the transfer function of a discrete time transversal filter can be changed or reconfigured by changing the optical power of the different taps according to an apodisation function. Therefore, a decrease in the secondary sidelobes of the filter can be achieved (Capmany *et al*., 1999a, 2005). It is also useful method for considerable reduction of secondary sidelobes (Capmany *et al*., 1999a). The different windowing profiles are described as follows: The Gaussian window is described by:

$$w(n) = e^{-\frac{1}{2}\left(\frac{n-\frac{(N-1)}{2}}{\frac{\sigma(N-1)}{2}}\right)^2}, \quad \sigma \le 0.5 \quad (4)$$

The Kaiser window description is given by:

$$w(n) = \begin{cases} \frac{I_0[\beta(1-[(n-\alpha)/\alpha)]^2)^{\frac{1}{2}}]}{I_0(\beta)} & 0 \le n \le N \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

Where:

N = Number of taps

α = N/2

$I_0(.)$ = Zeroth-order modified bessel function of the first kind and the tapering parameter is $\beta = 1.9$

The Hamming window is described by:

$$w(n) = 0.54 - 0.46\cos\left(\frac{2\pi n}{N-1}\right), \quad 0 \le n \le N \quad (6)$$

Then, the reconfigured transfer function of proposed filter by employing apodization is obtained by:

$$|Hwith\ Apod(\Omega)| = R\left|\sum_{m=1}^{N}\sum_{n=1}^{N} P_m w_m P_n w_n e^{-j\Omega[(m-1)(\Delta\tau 1)+(n-1)\Delta\tau 2]}\right| \quad (7)$$

RESULTS AND DISCUSSION

The layout of the proposed configuration of spectrum sliced mm-wave photonic filter using cascaded fabry-perot filters is shown in Fig. 2. The broadband spectrum from the optical source was amplified by means of Amplified Spontaneous Emission (ASE) generated by Erbium-Doped Fiber Amplifier (EDFA). The ASE output from EDFA1 is centered at a wavelength of 1531.8 nm was fed to first FP filter. A filter with 34 taps, differential delay between adjacent carriers of $\Delta\tau 1$ = 438 ps (= 17 ps/km.nm×92 km×0.28 nm) corresponds to FSR value of 2.3 GHz has been used.

A standard single mode optical fiber with 92 km length and dispersion factor D = 17 ps/km.nm was used. The output sliced spectrum of the first filter was fed as input to second fiber FP filter with same number of filter taps. The incremental differential delay of this filter is $\Delta\tau 2$ = 560 ps (=17 ps/km.nm×118 km×0.28 nm) corresponds to FSR value of 1.78 GHz. The second FP filter was designed to have the same dispersion factor of the first filter but the length of the fiber was 118 km. The output from the FP filters was fed to the optical dispersive element implemented by means of a coil of 46 km of single mode standard fiber with dispersion parameter D = 17 ps/km.nm and wavelength spacing of 0.28 nm. The output signal is amplified by EDFA2 and fed to a photodetector. The overall transfer function of the proposed architecture was derived and was implemented in the MATLAB simulation platform to view the results. The different FSR values of two FP filters in cascaded configuration gives the overall filter FSR is about 41.1 GHz (Jeyachitra and Sukanesh, 2010a).

Figure 3 shows the spectral characteristics of proposed configuration for the frequency range from 0-50 GHz with no apodization. It is obtained using the Eq. 3. It shows the overall filter FSR is at 41.1 GHz.

Figure 4 shows the frequency characteristics of the proposed filter with different FSR values of 2.3 and 1.78 GHz of individual filter in cascaded configuration, respectively with no apodization. It represents simulated frequency response of the proposed filter with no apodization. This figure plots normalised modulus of overall transfer function of the presented filter with frequency. The frequency response of the proposed filter is obtained by using MATLAB in Eq. 3. Under above conditions, the overall filter response shows a single resonance at 41.1 GHz frequency. The results show that this configuration has very good sidelobe rejection (Jeyachitra and Sukanesh, 2010a).

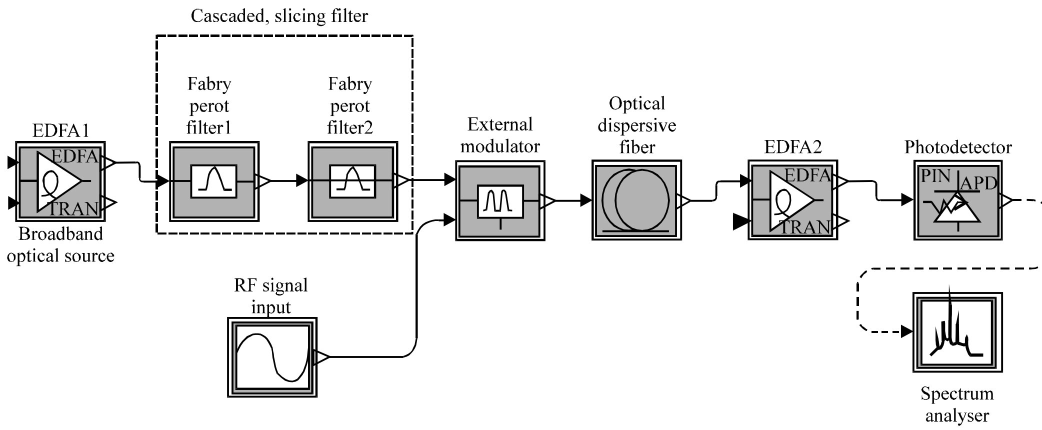

Fig. 2: Proposed configuration of spectrum sliced mm-wave photonic filter using cascaded fabry-perot filters

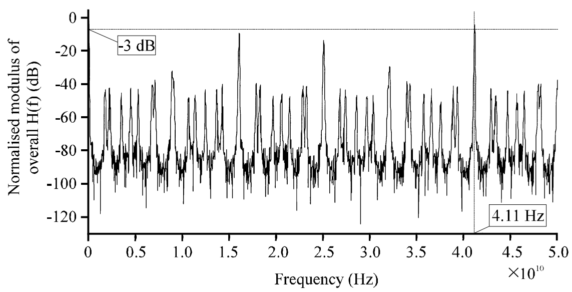

Fig. 3: Spectral characteristic of proposed configuration with the cascaded FP filters from DC to 50 GHz with no apodization

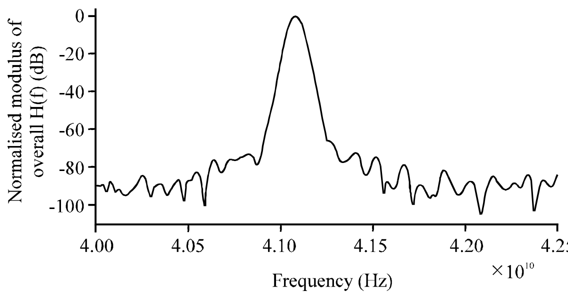

Fig. 4: Frequency characteristics of proposed configuration using cascaded FP filter with no apodization and having different FSR corresponds to Δτ1 = 438 ps and Δτ2 560 ps

Q-factor calculation: The Q-factor of the filter is given as Q-factor = (Overall FSR)/(3dB Bandwidth). The overall FSR of the filter is 41.1 GHz. The 3dB Bandwidth (≈f2-f1) of 50 MHz was obtained from Fig. 5. Thus, yielding Q-factor of 822 (Jeyachitra and Sukanesh, 2010a).

Reconfigurable filter using windowing techniques: The frequency characteristics of the proposed configuration

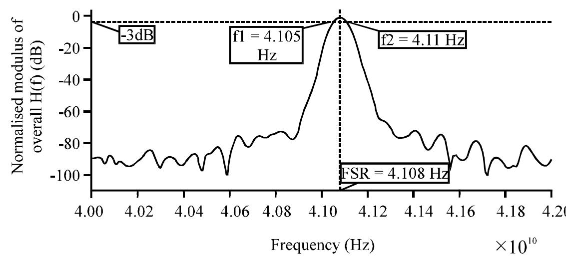

Fig. 5: Q-factor calculation of the proposed filter (Jeyachitra and Sukanesh, 2010a)

was achieved and analysed for different high profiled windowing techniques. The reconfigurability of the present filter was obtained by simulating the Eq. 7. A more efficient filter design can be achieved by the use of appropriate window functions (Capmany *et al*., 1999a). The experimental results of Capmany *et al*. (1999a, b) demonstrate the potential for filter reconfiguration for different apodization such as arbitrary weighting, Hamming and Hanning windows. The reconfigurability of the filter was demonstrated by employing multiple different high profiled windows which includes Gaussian, Kaiser, Hamming and Hanning windows. The reconfiguration capability of the proposed filter for different apodisation methods are analysed using different windowing techniques. The reconfigurable spectrum of the present filter is obtained by simulating the Eq. 7 using MATLAB. Figure 6-8 shows the reconfiguration capability of the proposed filter for different Apodization Methods and the results are compared with Jeyachitra and Sukanes (2010a).

Figure 6 is the reconfigured spectrum of mm wave photonic microwave filter using Gaussian window. Dotted line indicates the optical spectrum with Gaussian apodized and solid line shows that the filter frequency response without windowing technique. The filter centre

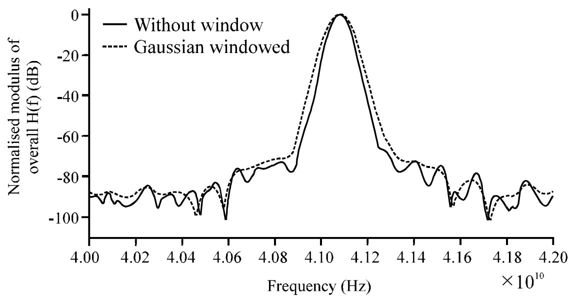

Fig. 6: Reconfigurable frequency response of millimeter wave photonic microwave filter using Gaussian window for the different incremental differential delay $\Delta\tau 1$ = 438 ps and $\Delta\tau 2$ = 560 ps

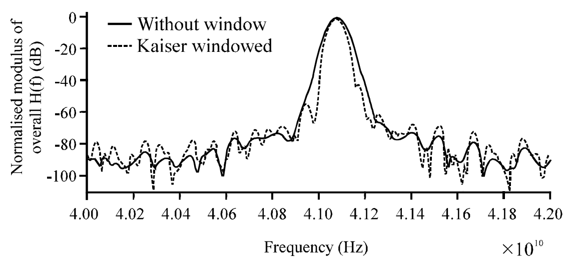

Fig. 7: Reconfigurable frequency response of millimeter wave photonic microwave filter using Kaiser window for the different incremental differential delay $\Delta\tau 1$ = 438 ps and $\Delta\tau 2$ = 560 ps

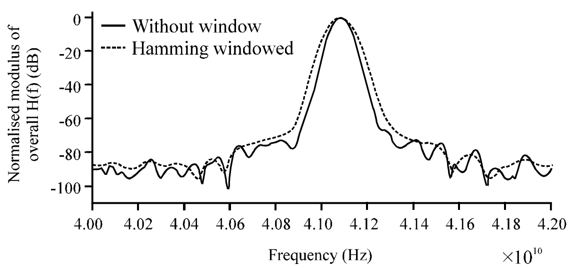

Fig. 8: Reconfigurable frequency response of millimeter wave photonic microwave filter using Hamming window for the different incremental differential delay $\Delta\tau 1$ = 438 ps and $\Delta\tau 2$ = 560 ps

frequency is measured for both spectrums as 41.1 GHz. The 3 dB BW is determined from the spectrum as 70 dB and its Q-factor is found to be as 587. It shows an excellent sidelobe rejection as 84 dB.

Another reconfigurable spectrum of spectrum sliced millimetre wave photonic filter using Kaiser window is presented in Fig. 7. Delay times of $\Delta\tau_1$ = 438 ps, $\Delta\tau 2$ = 560 ps are applied to two FP filters connected in cascaded form and its reconfigurability is obtained by

Table 1: Reconfigurable capabilities of mm-wave photonic filter

Type of apodization used	Overall filter FSR (GHz)	3dB BW (MHz)	Q-factor	MSSR (dB)
Without window	41.1	50	822	78
Gaussian window	41.1	70	587	84
Kaiser window	41.1	50	822	55
Hamming window	41.1	70	587	82

applying Kaiser window. Optical spectrum by employing Kaiser window is represented by blue dotted line and solid curve is filter response without windowing technique. The centre frequency of filter with and without apodization is same (41.1 GHz). Its 3 dB BW is measured as 50 MHz. Q-factor is found as 822 for this apodization technique. But it has low value of MSSR level (55 dB) compared to Gaussian windowed filter.

Figure 8 is the reconfigured spectrum of millimeter wave photonic microwave filter using Hamming window. Dotted line indicates the optical spectrum with Hamming apodized and solid line shows that the filter frequency response with windowing technique. The filter centre frequency is measured for both spectrums as 41.1 GHz. The 3 dB BW is determined from the spectrum as 70 dB and its Q-factor is found to be as 587. It is showing an excellent sidelobe rejection as 82 dB.

Table 1 summarizes the reconfigurable frequency response of the filter for multiple apodization techniques. From the Table 1, it is very clear that the filter centre frequency is same for all the three apodization techniques. An excellent sidelobe suppression level is obtained from Gaussian windowed filter. An overall filter with Kaiser window shows a very good reconfigurable capability than filter with other two windows interms of FSR, high Q-factor and good sidelobe rejection level. The results clearly show that it can be used for high density telecommunication networks and mm-wave photonic communication systems.

CONCLUSION

Researchers have developed and characterized a new mm-wave photonic filter operating in 40 GHz band. The high operating frequency was achieved by slicing the spectrum of a broadband optical source by cascaded fabry-perot filters with different FSRs. The simulated results have been analysed. It showed very good filter performances of overall filter passband response 41.1 GHz and 3 dB bandwidth is about 50 MHz. The quality factor of 822 and very high sidelobe rejection have been reported. This filter shows very good performances which makes the system as simple and cost effective. Besides simplicity and cost effective the proposed filter also features reconfigurability.

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