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X-band Microwave Photonic Filter Using Switch-based Fiber-Optic Delay Lines

Byung-Min Jung*

Radar·PGM R&D Center, Hanwha Systems, Yongin 17121, Korea

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An X-band microwave photonic (MWP) filter using switch-based fiber-optic delay lines has been proposed and experimentally demonstrated. It is composed of two electro-optic modulators (EOMs) and 2×2 optical MEMS-switch-based fiber-optic delay lines. By changing time-delay difference and coefficients of each wavelength signal by using fiber-optic delay lines and an electro-optic modulator, respectively, a bandpass filter or a notch filter can be implemented. For an X-band MWP filter with four channel elements, fiber-optic delay lines with the unit time-delay of 50 *ps* have been experimentally realized and the frequency responses corresponding to the time-delays has been measured. The measured frequency response error at center frequency and the time-delay difference error were 180 MHz at 10 GHz and 3.2 *ps*, respectively, when the fiber-optic delay line has the time-delay difference of 50 *ps*.

Keywords : Optical fiber delay line, Microwave photonic filter, True time-delay (TTD)
OCIS codes : (060.2330) Fiber optics communications; (060.4510) Optical communication

I. INTRODUCTION

Microwave photonic (MWP) filters have been investigated by many researchers because of their advantages for signal processing of microwave and millimeter-wave signals including low loss, light weight, and immunity electromagnetic interferences. In particular, MWP filters using optical delay lines unlike conventional electrical RF filters can provide large instantaneous bandwidth over 100 GHz, variable free spectral ratio (FSR), and the possibility of new spatial and wavelength opportunity because optical delay lines support very short time-delays, tunable time-delay difference, and wavelength division multiplexing (WDM) techniques [1, 2]. For implementation of MWP filters, numerous schemes using high dispersive fibers [3], uniform fiber Bragg gratings (FBGs) [4], FBGs and binary fiber delay lines [5], a multichannel chirped fiber grating [6], and a superstructured FBG [7] have been proposed and demonstrated. Among these, the scheme using the high dispersive fibers has the disadvantage of its bulky size for realization due to the fiber length corresponding to several km. The scheme using FBGs does not have the size problem, but it can only offer RF frequency response up to S-band due to a physical limitation imposed by the spacing between adjacent FBGs. On the other hand, the scheme using the multichannel chirped fiber grating can offer higher RF frequency response than S-band because continuous time-delay difference can be obtained from the chirped gratings. However, the multichannel chirped fiber gratings and the superstructured FBG have a disadvantage of difficulty in fabrication.

An optical true time-delay beam former using fiber-optic delay-lines for a planar phased array antenna was reported [8]. The structure of the beam former, realized in a scheme to adjust the switches simultaneously on a column-by-column basis by an electronic switch controller, offers advantages of low complexity, fast reconfiguration, and easy fabrication. Also, this structure can be easily scaled since there is no correlation between the columns of the fiber delay line in terms of time-delays unlike the structure using the binary fiber delay lines reported.

In this paper, we propose and demonstrate a novel X-band MWP filter using switch-based fiber optic delay lines with bandpass or notch filtering. The filtering is realized by changing coefficients of wavelength signals by using an electro-optic modulator (EOM) and time-delay

*Corresponding author: byungmin75.jung@hanwha.com, ORCID 0000-0003-2557-8258
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difference of wavelength signals by using fiber-optic delay lines. Base on the proposed scheme, a 4-lines × 2-bit switch-based fiber optic delay line matrix with a unit time-delay of 50 ps for a X-band MWP filter with four channel elements has been experimentally demonstrated.

II. PRINCIPLE

The schematic diagram of the proposed fiber optic delay line based MWP filter with negative or positive coefficients is shown in Fig. 1. The system consists of two groups of multiwavelength sources with λ_1, λ_3 … λ_{2n-1} and λ_2, λ_4 … λ_{2n}, two wavelength division multiplexing (WDM) multiplexers (MUX), two EOMs, a 1 × 2 optical coupler, an erbium-doped fiber amplifier (EDFA), a fiber optic delay line matrix consisting of 2 × 2 optical MEMS switches with fiber delay lines connected between CROSS ports, a couple of DEMUX and MUX, and a photodetector (PD). Upper and lower groups of the multiwavelength sources are fed to each upper and lower EOM and then combined by a 1 × 2 optical coupler. The upper group is modulated at positive bias voltage in ihe upper EOM, whereas the lower group is modulated at the same or opposite bias voltage in the lower EOM, to accomplish frequency responses of a MWP filter with positive or negative coefficients as can be seen Fig. 1. The modulated signals from the EOMs are combined into a 1 × 2 optical coupler and amplified by the EDFA, and then launched into the fiber optic delay line to obtain a required time-delay for each wavelength signal. When all the MEMS switches in the fiber optic delay line are in a BAR state, time difference between modulated optical signals are identical. Time-delay provided by the fiber optic delay line matrix increases by $\Delta\tau$ from the top row to the bottom one. Time-delay increments in the first, second, and third columns are $\Delta\tau$, $2\Delta\tau$, and $4\Delta\tau$, respectively. Thus, in the m-th column, the delay increment becomes $2^{(m-1)}\Delta\tau$. In this scheme, the switch controller sets all the MEMS switches in a column to either BAR or CROSS state simultaneously. The proposed filter can be used as a tunable bandwidth or notch filter by changing the coefficients of the modulated optical signals based by the EOM and the time-delay difference of the modulated optical signals by the fiber optic delay line matrix, as shown in Fig. 1.

III. EXPERIMENT AND RESULTS

To prove the concept of the proposed technique, a MWP filter is experimentally realized. Figure 2 shows the experimental setup to measure frequency responses of the proposed filter. The two fixed wavelength signals having wavelengths of $\lambda_1 = 1549.32$ and $\lambda_3 = 1550.92$ nm are multiplexed and then modulated with the RF signal by the EOM1 with the positive bias voltage of V_bias_Po = 2.0 V. The other two wavelength signals having wavelengths of $\lambda_2 = 1550.12$ and $\lambda_4 = 1551.72$ nm are multiplexed and then modulated with the RF signal by the EOM2 with the positive bias of V_bias_Po = 2.0 V or the negative bias of V_bias_Ne = 4.0 V for an inverted output signal. The RF signal modulating the four optical signals with different wavelengths is provided by a vector network analyzer (VNA). The modulated signals are combined by the 1 × 2 optical coupler and amplified by the EDFA having the gain of 10 dB, and then demultiplexed and launched into the 4-lines × 2-bit fiber optic delay line. For implementation of a 10 GHz MWP bandpass or notch filter, the unit time delay difference of $\Delta\tau = 50$ *ps* is chosen. The time-delay difference between adjacent wavelength signals shown in Fig. 2 can be obtained as one of 0 (BAR-BAR), $\Delta\tau$ (CROSS-BAR), $2\Delta\tau$ (BAR-CROSS) and $3\Delta\tau$ (CROSS-CROSS) since the 2 × 2 optical switches in the delay lines with the time-delay increments of $\Delta\tau$ and $2\Delta\tau$ for the first and second columns are simultaneously adjusted on a column-by-column basis. A bandpass or a notch filter with

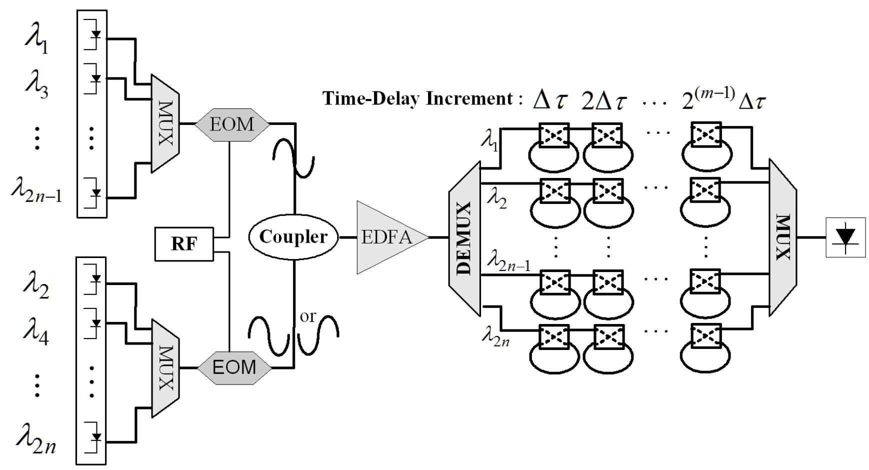


FIG. 1. Schematic diagram of the proposed fiber optic delay line based microwave photonic filter with negative or positive coefficients.

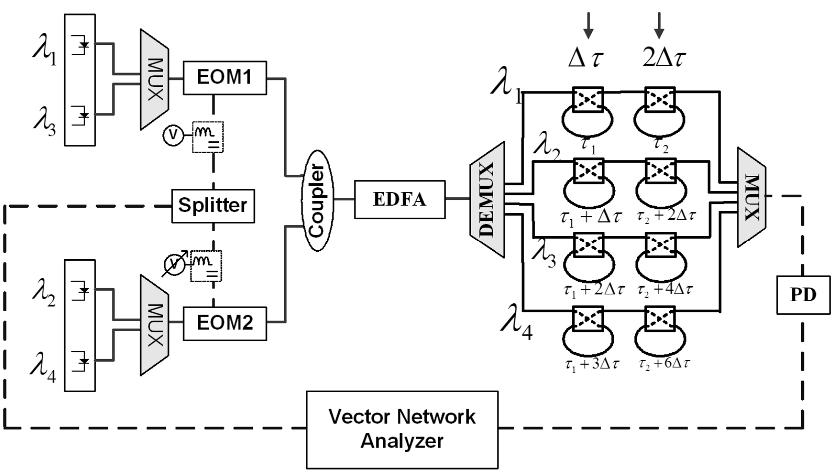
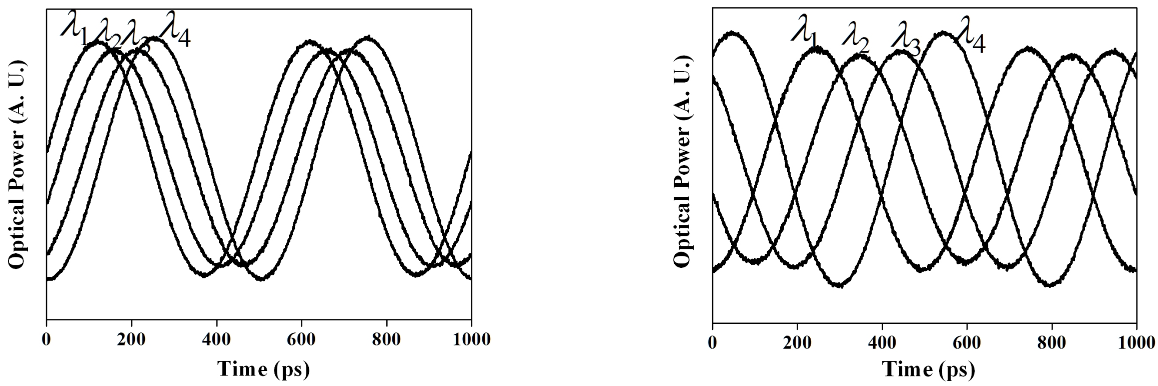


FIG. 2. Experimental setup for the frequency response measurement of the proposed microwave photonic filter.



(a) (b)

FIG. 3. Measured waveforms with time-delay difference generated by the fiber optic delay line (a) CROSS-BAR state (b) BAR-CROSS state. The EOM1 and EOM2 are biased at 2.0 V.

a center frequency at 10 GHz can be obtained since the FSR is inversely proportional to the unit time delay difference of 50 ps. Finally, the four modulated optical signals are multiplexed, converted to electrical signals by a PD, and then monitored by the VNA.

The time delays generated by the fiber optic delay lines in Fig. 2 are measured. Figure 3 shows the measured waveforms of four modulated optical signals generated by the 4-lines × 2-bit fiber optic delay line matrix when a sinusoidal signal ($f_{RF} = 2$ GHz) is applied to the EOMs biased at 2.0 V. By using a digital sampling oscilloscope after the optical PD and replacing the RF source with a RF signal generator, four time delayed signals can be measured. Figure 3(a) shows the waveforms of four time-delayed signals when the columns in the fiber optic delay line are in the CROSS-BAR state. At this time, the time-delay differences between the adjacent wavelength signals are 50 ps as shown in Fig. 2. The measured time-delay difference between λ_1 and λ_2 is 48.4 ps, 53.2 ps between λ_2 and λ_3, 51.6 ps between λ_3 and λ_4. Figure 3(b) shows the four RF waveforms with a time-delay difference generated by the second column when the columns are BAR-CROSS states. The measured time-delay differences between adjacent wavelength signals are 98.5 ps, 100.7 ps and 102.2 ps respectively. The time-delay difference errors are caused by the jitter between different wavelength signals and the fabrication error of the fiber optic delay lines.

Figure 4 shows the simulated and the measured frequency responses for the proposed MWP filter when $V_{EOM1} = 2.0$ V, $V_{EOM2} = 4.0$ V. The solid lines in Fig. 4 correspond to the theoretical frequency responses in the RF frequency range from 0 GHz to 20 GHz. The dots are measured frequency responses of the filter in the frequency range from 4 GHz to 16 GHz. The measured frequency range has been chosen above and below from 10 GHz, since the unit time delay difference of the fiber optic delay line in Fig. 2 was 50 *ps* to implement a 10 GHz bandpass or notch filter. Figures 4(a)~4(c) show the frequency responses of the bandpass filter since λ_1 and λ_3 are modulated at positive bias voltage of 2.0 V, and λ_2 and λ_4 are modulated at negative bias voltage of 4.0 V as we have seen in Fig. 1. Those in Figs. 4(a)~4(c) are the frequency responses

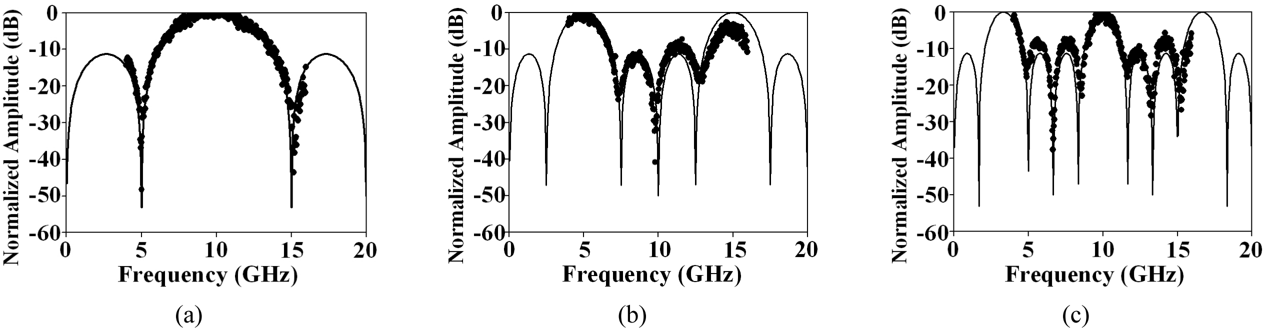


FIG. 4. The frequency responses of the proposed filter when V_{EOM1} = 2.0 V, V_{EOM2} = 4.0 V and the columns of the fiber optic delay line are in the (a) CROSS-BAR states (b) BAR-CROSS states (c) CROSS-CROSS states. Theory (solid line) and Experiment (dot).

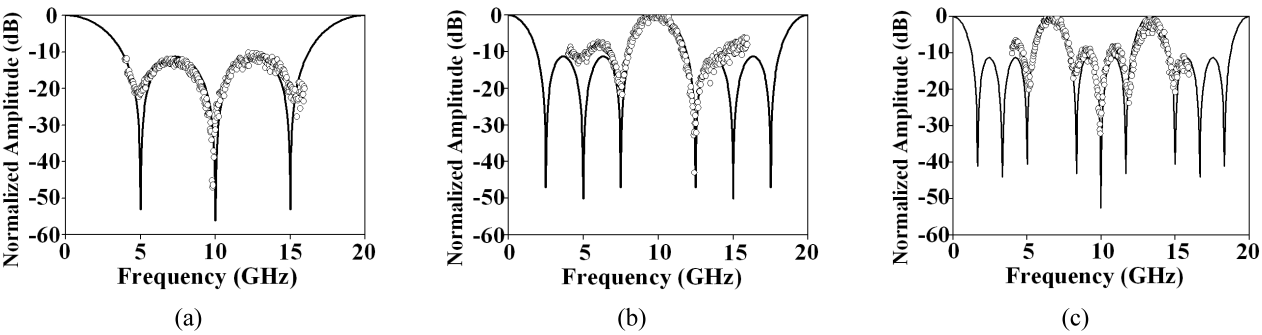


FIG. 5. The frequency responses of the proposed filter when V_{EOM1} = 2.0 V, V_{EOM2} = 2.0 V and the columns of the fiber optic delay line are in the (a) CROSS-BAR states (b) BAR-CROSS states (c) CROSS-CROSS states. Theory (solid line) and Experiment (hole).

when the columns of the fiber optic delay line are in the CROSS-BAR, BAR-CROSS and CROSS-CROSS states, respectively. The simulated and the measured 3 dB bandwidths at 10 GHz in Fig. 4(a) are 4.56 GHz, 4.16 GHz and 1.52 GHz, 1.20 GHz in Fig. 4(c) respectively. The simulated and the measured center frequencies in Fig. 4(b) are 10.00 GHz and 9.84 GHz. The simulated main to secondary sidelobe ratio (MSSR) for all cases is 11.3 dB. The measured MSSR in Fig. 4(b) and (c) are 7.5 dB. The 3 dB bandwidth error and center frequency error for the proposed bandpass and notch filters are caused by the time-delay difference errors of the modulated optical signals in the fiber-optic delay lines. Also, the MSSR error is caused by the large insertion loss of the system and different signal amplitude.

Figure 5 shows the simulated and the measured frequency responses for the proposed MWP filter when V_{EOM1} = 2.0 V, V_{EOM2} = 2.0 V. The solid lines in Fig. 5 correspond to the theoretical frequency responses in the RF frequency range from 0 GHz to 20 GHz. The holes are measured frequency responses of the filter in the frequency range from 4 GHz to 16 GHz. Unlike Figs. 4(a)~4(c), Figs. 5(a)~5(c) show the frequency responses of the lowpass filter since all wavelength signals have positive coefficients as modulated at same bias voltage. Figures 5(a)~5(c) show the frequency responses of the lowpass filter when the columns of the fiber optic delay line are in the CROSS-BAR, BAR-CROSS and CROSS-CROSS states, respectively. The simulated and the measured 3 dB bandwidths at 10 GHz in Fig. 5(b) are 2.30 GHz and 2.19 GHz. The simulated center frequency in Figs. 5(a) and 5(c) are 10.00 GHz, and the measured center frequencies are 9.82 GHz and 9.93 GHz, respectively. The measured MSSR in Figs. 5(b) and 5(c) are 7.1 dB. The reason for the 3 dB bandwidth error and center frequency error of the frequency responses of the lowpass filter in Fig. 5 are similar to that in Fig. 4. The measured frequency response errors at center frequency in Figs. 4(a) and 5(a) are larger than those in Figs. 4(b) and 5(b) because the time-delay difference error in Fig. 3(a) is larger than that in Fig. 3(b). The maximum frequency response error at center frequency and the time-delay difference error were -180 MHz at 10 GHz and 3.2 ps between λ_2 and λ_3 respectively, when the time-delay difference of the fiber optic delay line is 50 ps. If the time-delay difference error and insertion loss of the system are decreased, the characteristics of the proposed filter will be improved.

IV. CONCLUSION

MWP filter based on a fiber optic delay line have been demonstrated. In the experimental results, the feasibility of bandpass or lowpass filters with the variable FSR by changing the state of the MEMS switches with simple electric control was described. A 4-lines × 2-bit switch-based fiber optic delay line with a unit time-delay of 50 ps is used for the X-band MWP filters with four channel elements. The maximum time-delay difference error of the fiber optic delay line is as small as 3.2 ps, which corresponds to the maximum frequency response error of 600 MHz at center frequency for a 10 GHz MWP filter. The measured frequency response error is less than 180 MHz in the RF frequency range from 4 GHz to 16 GHz. From the experimental results, the applicability of radar systems with the MWP filter using the fiber optic delay lines has been implemented.

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