Polarization-Independent, Multifunctional All-Fiber Comb Filter Using Variable Ratio Coupler-Based Mach–Zehnder Interferometer

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***Abstract*—A polarization-independent, multifunctional all-fiber comb filter by using variable ratio coupler (VRC)-based dual-pass Mach–Zehnder interferometer is newly proposed and demonstrated. Depending on the dynamic settings of coupling ratios of the fiber couplers, the comb filter provides the channel spacing tunable, multiwavelength switchable, and flat-top spectral responses. Theoretical calculations are verified by the experimental results. Experimentally, a comb filter with the channel spacing tunable from 0.4 to 0.8 nm was obtained. Meanwhile, when the comb spacing was tuned to 0.8 nm, the multiwavelength switchable operation with both the sinusoid and flat-top spectral responses was achieved. The proposed comb filter may find applications in optical communication systems and tunable multiwavelength fiber lasers.**

***Index Terms*—Comb filter, Mach–Zehnder (M–Z) interferometer, multifunction, polarization-independent.**

I. Introduction

DENSE wavelength-division-multiplexing (DWDM) optical network has been considered as an economical and efficient way of meeting the future need for the increasing capacity of communication system. Periodic optical comb filters are the key components in DWDM optical systems since they can be used to process the optical signal and isolate the neighboring channel signals to decrease the crosstalks. Apart from the use of a signal processor in DWDM systems, comb filters can also find important applications in multiwavelength laser sources because they are the wavelength selective elements for the generation of multiwavelength lasing lines. Therefore, the comb filters have attracted much attention in recent years. Especially, the comb filters with all-fiber design offer the advantages such as low insertion loss, low cost, and good compatibility with the fiber communication systems. However, a specific comb filter generally has fixed spectral response, which cannot meet the requirement of tunability in some applications.

To enhance the functionality and the flexibility of a comb filter, many efforts have been directed toward investigating the tunability of a comb filter including channel spacing tunable and multiwavelength switchable operations. So far, different approaches have been proposed to construct a tunable fiber comb filter, such as using polarization diversity loop [1]–[4], Lyot configuration [5]–[8], a modified Mach–Zehnder (M–Z) interferometer [9], fiber Bragg grating [10]–[16], and Sagnac birefringence loop [17]–[22]. However, the transmission bands of the comb filters mentioned previously are not flat which have sinusoid shapes. On the other hand, in order to relax the wavelength control in DWDM systems, the all-fiber flat-top comb filter is more favorable for the tolerance of signal wavelength drift and signal fidelity. To date, the all-fiber flat-top comb filter can be implemented, for example, by using cascaded high birefringence fiber [23], fiber Bragg grating [24], [25], and birefringence combination Sagnac loop [26]. Therefore, it would be interesting to know whether the multifunctional spectral responses such as channel spacing tunable, multiwavelength switchable, and flat-top operations can be simultaneously realized in an integrated comb filter.

As for some practical applications, the input polarization-independent characteristic of a comb filter is also important since the polarization state of the signal is random in communication systems [27], [28]. Although some of the comb filters discussed previously are polarization independent, they may need to adjust the polarization state inside the comb filter to tune the spectral response. The random birefringence of single-mode fiber (SMF) in the comb filter might change the polarization state of light along the fiber, thus resulting in the less efficient operation. Recently, we have reported a few techniques to enable the modified M–Z interferometer to possess different functions such as channel spacing tunable [29], [30], multiwavelength switchable [31], and flat-top [32] operations. However, a rotatable polarizer should be employed at the input port to realize all the functions, indicating that the comb filters are polarization dependent. Thus, the efficiency and the structural simplicity of the comb filter could be overshadowed by the use of the polarizer.

In this paper, we propose and demonstrate a polarization-independent multifunctional comb filter using a variable ratio coupler (VRC)-based dual-pass M–Z interferometer. No polarization-dependent device is required to control the comb spectrum,

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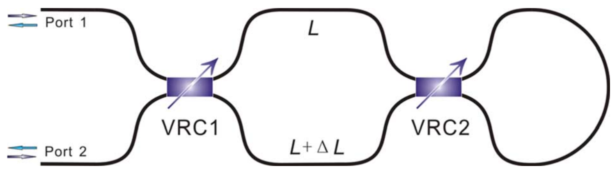

Fig. 1. Schematic of the proposed multifunctional comb filter.

which makes the comb filter polarization independent and efficient design. By simply adjusting the coupling ratios of the VRCs, the channel spacing tunable between single- and dual-pass M–Z interferometer, multiwavelength switchable (interleaving), and flat-top spectral responses can be efficiently obtained in an integrated comb filter. Theoretical predictions were verified by the experimental results.

II. Experimental Setup and Operation Principle

Fig. 1 shows the schematic of the proposed multifunctional all-fiber comb filter. The comb filter design is developed from a conventional dual-pass M–Z interferometer. However, instead of using two 3 dB fiber couplers, the proposed comb filter consists of two VRCs whose coupling ratio can be continuously tuned from 0–100%. The pigtails of two VRCs are all SMFs. As can be seen in Fig. 1, no polarization-related component needs to be used to tune the spectral response, suggesting that the proposed comb filter is polarization independent. Moreover, in order to test the transmission characteristics of the comb filter, we employed an amplified spontaneous emission light source as the input in Port 1.

First, the transmission characteristics of the proposed VRC-based multifunctional comb filter are theoretically analyzed. Since the input is polarization independent, we assume that the arbitrary light is launched into the input port 1. The spectral response of the proposed comb filter can be analyzed by the following Jones matrix representation:

$$\begin{bmatrix} E_{1\text{out}} \\ E_{2\text{out}} \end{bmatrix} = [C_1][F][C_2][R][C_2][F][C_1][E_{\text{in}}]. \quad (1)$$

In (1), $[E_{\text{in}}]$ is the input field of the comb filter, and $[C_i]$ $(i = 1, 2)$ and $[F]$ denote the matrices of the fiber couplers and the interferometer arms, respectively. Then, we used the following matrix representations in the calculation of (1):

$$[E_{\text{in}}] = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$
$$[C_i] = \begin{bmatrix} \sqrt{1-c_i} & j\sqrt{c_i} \\ j\sqrt{c_i} & \sqrt{1-c_i} \end{bmatrix} \ (i = 1, 2)$$
$$[F] = \begin{bmatrix} e^{j\phi} & 0 \\ 0 & 1 \end{bmatrix}, \quad [R] = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}.$$

Here, c_i is the coupling ratio of the fiber coupler; $\phi = kn\Delta L$ is the phase difference due to the path difference between the two interferometer arms, where n and ΔL are the fiber refractive index and the length difference between two arms, respectively. Note that the polarization-dependent loss (PDL) of the VRCs used in our experiment can be neglected; thus, the PDL was not considered in the theoretical calculation. Substituting the aforementioned matrices representations into (1), and then, the transmission functions of the output ports are obtained

$$\begin{aligned} T_{1\text{out}} &= |E_{1\text{out}}|^2 \\ &= [4c_1^2 c_2(1-c_2) \\ &\quad + 4c_2(1-c_1)^2(1-c_2) \\ &\quad + 4c_1(1-c_1)(1-2c_2)^2] \\ &\quad + 8(1-2c_1)(1-2c_2) \\ &\quad \times \sqrt{c_1 c_2(1-c_1)(1-c_2)} \cos\phi \\ &\quad - 8c_1c_2(1-c_1)(1-c_2)\cos 2\phi \end{aligned} \quad (2a)$$

$$\begin{aligned} T_{2\text{out}} &= |E_{2\text{out}}|^2 \\ &= [8c_1c_2(1-c_1)(1-c_2) \\ &\quad + (1-2c_1)^2(1-2c_2)^2] \\ &\quad - 8(1-2c_1)(1-2c_2) \\ &\quad \times \sqrt{c_1 c_2(1-c_1)(1-c_2)} \cos\phi \\ &\quad + 8c_1c_2(1-c_1)(1-c_2)\cos 2\phi. \end{aligned} \quad (2b)$$

As can be seen in (2), the last two terms of both (2a) and (2b) include two periodic comb spectra that are corresponding to the single- $(\cos\phi)$ and dual-pass $(\cos 2\phi)$ standard M–Z interferometer, respectively. Moreover, the channel isolations of these two periodical comb spectra are related to the coupling ratio settings. Therefore, the transmission characteristics of the proposed comb filter are not only dependent on the phase delay ϕ between the two interferometer arms, but also on the coupling ratio c_i. Since the comb spectrum of the proposed filter is the combination of these two periodic comb spectra, by adjusting the coupling ratios, the spectral characteristics of the comb filter can be changed which is beneficial to the achievement of multifunctional spectral responses. In the following, the output port 1 is analyzed. For better analyzing the characteristics of the proposed comb filter, the first, second, and third terms of 2(a)) are denoted as *A*, *B*, and *C*, respectively. Therefore, 2(a) can be expressed as

$$T_{1\text{out}} = |E_{1\text{out}}|^2 = A + B + C \quad (3)$$

where

$$\begin{aligned} A &= [4c_1^2 c_2(1-c_2) \\ &\quad + 4c_2(1-c_1)^2(1-c_2) \\ &\quad + 4c_1(1-c_1)(1-2c_2)^2] \\ B &= 8(1-2c_1)(1-2c_2) \\ &\quad \times \sqrt{c_1 c_2(1-c_1)(1-c_2)} \cos\phi \\ \text{C} &= -8c_1c_2(1-c_1)(1-c_2)\cos 2\phi. \end{aligned}$$

In (3), term *A* is a dc component which only contributes to the intensity of the transmission. However, there are two periodical functions $[\cos\phi, \cos 2\phi]$ in terms *B* and *C* that influence the spectral response of the comb filter. Here, terms *B* and *C* represent two comb spectra. As clearly shown in term *B*, when $c_1 = c_2 = 0.5$, term *B* is equal to 0, indicating that the periodical function of $\cos\phi$ disappears. Thus, in this case, the proposed comb filter acts as a standard dual-pass M–Z interferometer whose channel spacing is determined by $\cos 2\phi$, which has

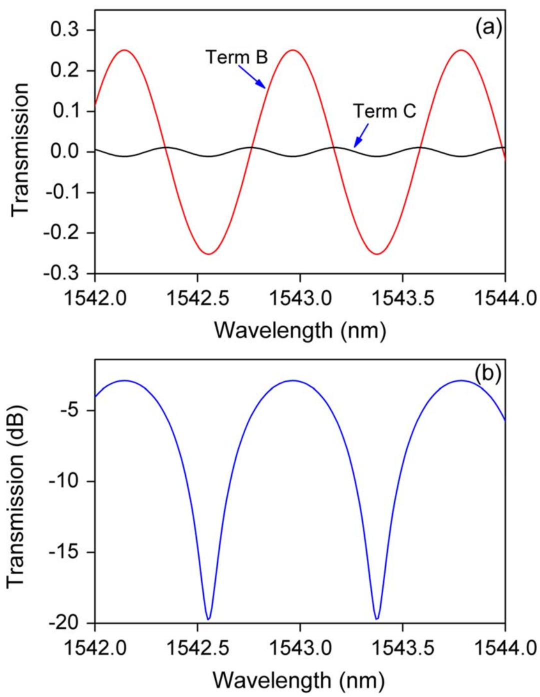

Fig. 2. (a) Calculated transmission curves of terms B (red) and C (black) in the case of $c_1 = 0.03 \mathrm{and} c_2 = 0.95$. (b) Corresponding total transmission spectrum of output port 1.

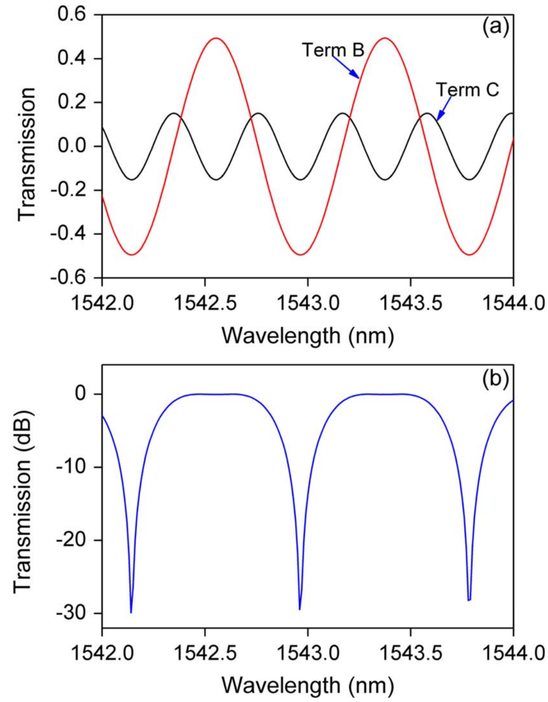

Fig. 3. (a) Calculated transmission curves of terms B (red) and C (black) in the case of $c_1 = 0.16 \mathrm{and} c_2 = 0.17$. (b) Corresponding total transmission spectrum.

been well known before [33]. However, as discussed previously, when the coupling ratio is tuned, the channel isolations of the two periodic comb spectra of terms B and C vary. Note that either of the two periodical functions can be eliminated or sufficiently be small by setting proper values of the coupling ratios. Therefore, one can decide which period of comb spectrum dominates the total spectral response. Suppose that the channel isolation of the comb spectrum determined by $\cos\phi$ is high enough and the other one $(\cos 2\phi)$ is low, i.e., $c_1 = 0.03,\ c_2 = 0.95$. Thus, the comb period of total spectral response is dominated by term $B\,(\cos\phi)$. To more clearly show this point, we have plotted the transmission curves of terms B and C in Fig. 2(a). As can be seen in Fig. 2(a), the linearly spectral contrast ratios of terms B and C are ~0.5 and ~0.02, respectively, indicating that term C contributes to the total spectral output much less than that of term B. In this case, the comb filter acts as a single-pass M–Z interferometer, as shown in Fig. 2(b). Based on the aforementioned discussions, the channel spacing tunable from dual- to single-pass one could be achieved by simply adjusting the coupling ratios, i.e., from $c_1 = c_2 = 0.5$ to $c_1 = 0.03, c_2 = 0.95$. When the channel spacing is tuned to the single-pass one, it is worthy to note that the sign of the periodical function $\cos\phi$ can be changed, but keep the same spectral shape by substituting $c_2' = 1 - c_2$ into (2a). When the sign of the periodical function alters, the multiwavelength switchable (interleaving) comb spectrum is obtained.

By further analyzing terms B and C, it is found that the stopband of the term $C\,(\cos 2\phi)$ exactly aligns with the passband of the term $B\,(\cos\phi)$. Therefore, the stopband of term C can counteract the maximum transmission intensity of term B, making that it is possible to obtain the flat-top spectral response whose comb period is determined by term $B\,(\cos\phi)$. Provided that the stopband of term C exactly counteracts the passband of term B by properly setting the channel isolations of these two comb spectra, the flat-top spectral response is achieved. For example, when $c_1 = 0.16, c_2 = 0.17$, the flat-top response of the comb filter can be obtained. Fig. 3(a) shows the spectral response of terms B and C in this case. Consider term A is a dc component; thus, the total output of port 1 is flat-top spectral response, as shown in Fig. 3(b). As mentioned previously, the multiwavelength switchable operation with flat-top response can be also attained by adjusting the coupling ratio of VRC_2 from c_2 to $c_2' = 1 - c_2$.

Therefore, by simply setting the coupling ratios of the fiber couplers, the proposed comb filter possesses some interesting transmission characteristics: 1) the channel spacing can be tuned between the standard single- and dual-pass M–Z interferometer; 2) it provides the multiwavelength switchable function; and 3) it serves as a flat-top comb filter.

III. Results and Discussions

Based on the aforementioned theoretical analysis, we show the calculated transmission spectra of output port 1 in the following. Here, $n = 1.46$ and $\Delta L = 2$ mm are used in the calculations, indicating that the channel spacings of both 0.4 and 0.8 nm can be obtained from the proposed comb filter. First, we concentrated on the channel spacing tunable and multiwavelength switchable functions with sinusoid spectral response. Fig. 4 presents the evolution of channel spacing tunable operation. The channel spacings are 0.4 and 0.8 nm in Fig. 4(a) and Fig. 4(c), respectively. Correspondingly,

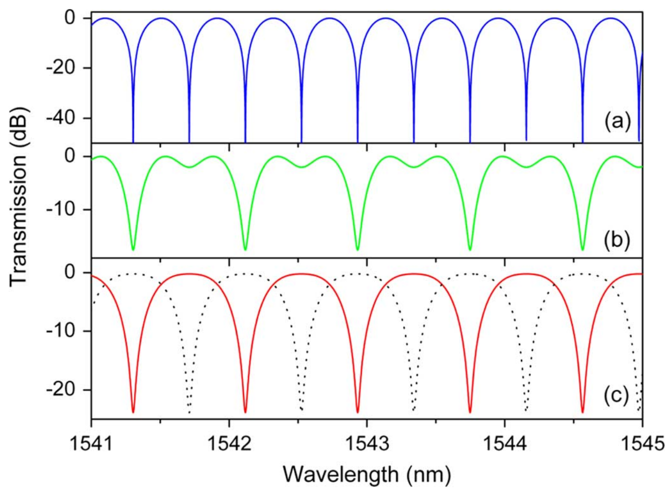

Fig. 4. Calculated transmission spectra of channel spacing tunable and multiwavelength switchable operations with sinusoid response.

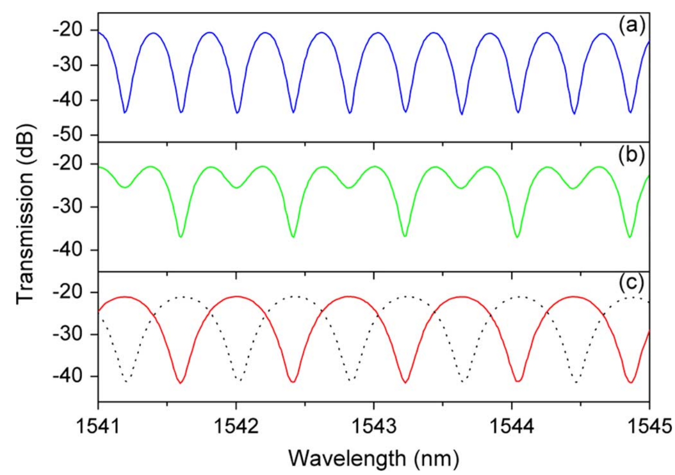

Fig. 6. Experimentally measured evolution of channel spacing tunable and multiwavelength switchable operations.

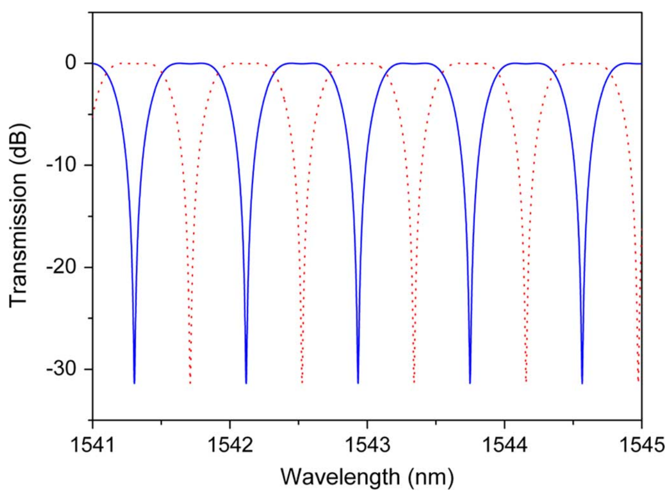

Fig. 5. Theoretically calculated curves of multiwavelength switchable flat-top operation.

$[c_1, c_2]$ are set to be $[0.5, 0.5], [0.25, 0.31]$, and $[0.13, 0.11]$, respectively. During the channel spacing tunable process, if the channel isolation of the comb spectrum determined by $\cos 2\varphi$ is not low enough, the comb spectrum exhibits two transmission peaks in one period, as shown in Fig. 4(b). When the channel spacing is tuned to 0.8 nm, we fixed the coupling ratio c_1 and just changed coupling ratio of VRC_2 from c_2 to $1 - c_2$ (from 0.11 to 0.89), and the multiwavelength switchable operation with 0.8 nm channel spacing is obtained, as shown in Fig. 4(c) with black dotted curve. By further adjusting the coupling ratios, i.e., $c_1 = 0.16 \text{and} c_2 = 0.17$, the flat-top comb spectrum is obtained, as shown in Fig. 5 with blue curve. Here, the channel spacing and the 1 dB bandwidth is 0.8 nm and ∼0.41 nm, respectively, indicating that the flat-top passband of 1 dB bandwidth extends to about 50% of the spectral spacing. As discussed previously, the comb filter provides the multiwavelength switchable function with 0.8 nm channel spacing by tuning the coupling ratio of VRC_2. Therefore, the multiwavelength switchable flat-top operation can be achieved with $c_1 = 0.16$ and $c_2 = 0.83$, as shown in Fig. 5 with red dotted curve.

In order to verify the theoretical prediction of the proposed comb filter, we constructed a comb filter depicted in Fig. 1 and measured the spectral response with different coupling ratios. A circulator was placed in the port 1 to extract the output light. The coupling ratios of two VRCs (Evanescent Optics Inc., Oakville, ON, Canada) are manually controlled. In addition, the polarization crosstalk is nearly zero and can be neglected. Since the channel spacing is determined by the path difference between the interferometer arms [33], the length of fiber pigtails of VRCs were carefully calculated and selected to guarantee that the channel spacing can be tuned between 0.4 and 0.8 nm. In the experiment, the two arms of M–Z interferometer were spliced by using a commercial fiber fusion splicer. First, both the coupling ratios were set to be 0.5; thus, the comb filter is a standard dual-pass M–Z interferometer corresponding to the 0.4 nm channel spacing in our experiment. Then, we adjusted the coupling ratios carefully and observed the spectral response of the proposed comb filter. Fig. 6 shows the experimental demonstration of channel spacing evolved from 0.4 to 0.8 nm and the multiwavelength switchable operation with 0.8 nm channel spacing. Note that the channel isolations of both theoretical and experimental results change during the channel spacing tunable operation. It is because that the channel isolations are related to the coupling ratios of VRCs, which can be analyzed from (2a). When the coupling ratios were further carefully tuned, the multiwavelength switchable flat-top spectral response was obtained, as shown in Fig. 7.

The experimentally obtained multifunctional spectral responses of the comb filter are well consistent with the theoretical predictions. The typical insertion loss of the comb filter was measured to be about 1.5 dB, which was mainly from the connection loss between fiber ferrules. It should also be noted that the experimentally obtained channel isolation of the comb filter is lower than that obtained in the calculations. However, they can be improved by carefully tuning the coupling ratios and reducing the connection loss of optical components. We have also investigated the dispersion of the comb filter. It was

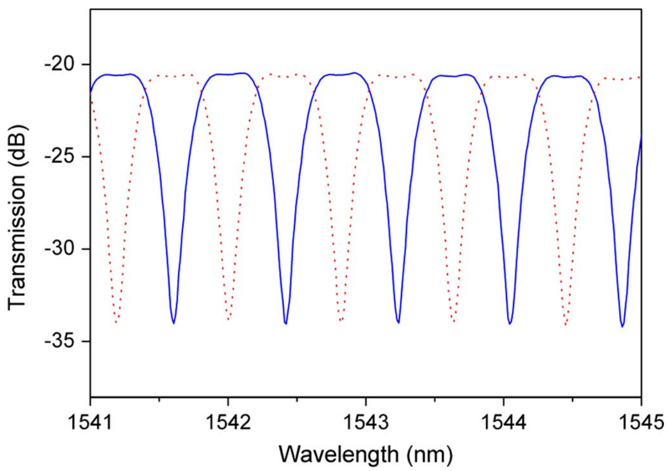

Fig. 7. Experimental observation of multiwavelength switchable flat-top operation.

found that the dispersion is dependent on the coupling ratio settings. Typically, the dispersion in the passband keeps below 20 ps/nm. For example, when $c_1 = c_2 = 0.15$, the dispersion is $|D| \leq 15.3$ ps/nm. In the experiment, the comb filter was packaged into a box to avoid the environmental perturbations. The maximum wavelength drift was ~0.02 nm, suggesting that the comb filter operated stably. Since the manually controlled VRCs were used in our experiment, therefore, for improving the tunable precision and speed, we can replace the manually controlled VRCs with electrically driven ones.

IV. Conclusion

We have demonstrated a polarization-independent, multifunctional all-fiber comb filter by using a VRC-based dual-pass M–Z interferometer. Via simply adjusting the coupling ratios, the channel spacing tunable, multiwavelength switchable, and flat-top spectral responses can be efficiently realized. Theoretical calculations were also verified by the experimental results. Such a multifunctional comb filter possesses the advantages of input polarization independence, low insertion loss, and high channel isolation, which may find some important applications in optical communication systems, such as processing of the optical signals and realization of tunable multiwavelength fiber laser.

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