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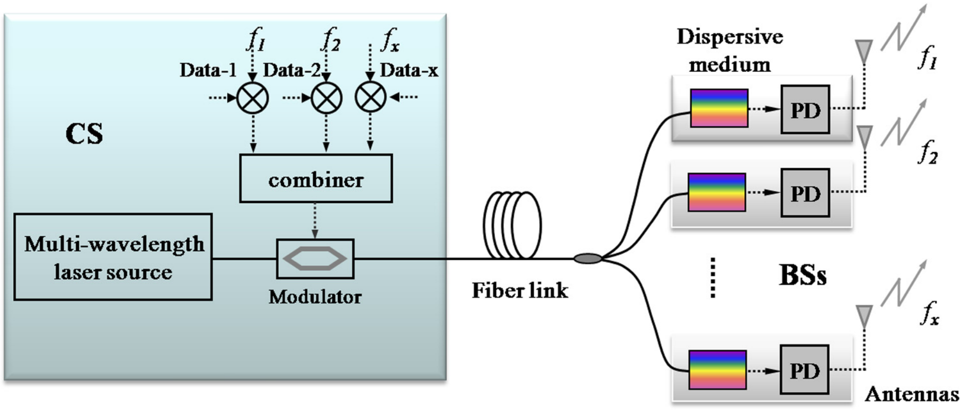

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Radio-over-Fiber System With Multiple-Optical-Source-Based Microwave Photonic Filter Performing as a Subcarrier Demultiplexer

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Abstract: A simple and cost-effective demultiplexing approach for a subcarrier multiplexed radio-over-fiber (RoF) system is proposed, analyzed, and experimentally demonstrated. A microwave photonic filter based on multiple optical sources is integrated into the RoF system, and by simply controlling the time delay in the remote antenna unit, the subcarrier with desirable frequency can be filtered out, and undesirable ones are suppressed. An experimental demonstration has been carried out by implementing a two-optical-source-based microwave photonic filter in an RoF downlink transmitting a 2.5-GHz subcarrier modulated with 150-Mb/s on-off keying (OOK) data, showing that it works well as a subcarrier demultiplexer. The proposed demultiplexing approach enjoys high flexibility, tunability, and cost-effectiveness and has good potential applications in the multiplexed RoF systems.

Index Terms: Radio-over-fiber (RoF) systems, microwave photonic filter, subcarrier demultiplex, multiple optical sources.

1. Introduction

Microwave photonics has attracted much research attention during the last two decades, due to its combining the advantages of both wireless communications and photonics, such as the mobility of wireless communications, large bandwidth, low loss, lightweight, and immunity to electromagnetic interference. Recently, microwave photonics has been explored more intensively at the subsystem and application levels. Many microwave photonic filter architectures [1]–[3] have been developed for particular applications, e.g., a tunable microwave photonic filter for noise and interference suppression in Universal Mobile Telecommunications System base stations has been reported [4].

In radio-over-fiber (RoF) systems, subcarrier multiplexing technology can further enhance the system transmission capacity. In the central station (CS), subcarriers with different frequencies are modulated by different kinds of data streams, and then, these subcarriers are transmitted through one fiber link to the remote antenna units (RAUs) [5]. In each RAU, a demultiplexing module should be available to pick up its own data stream, and one microwave filter can be employed as the demultiplexer. However, when the subcarrier frequency increases, e.g., in microwave/millimeter-wave (mmW)-over-fiber systems, the frequency could be up to 60 GHz, the traditional electrical microwave filter is hard to implement, or is very expensive. As the key advantage of the

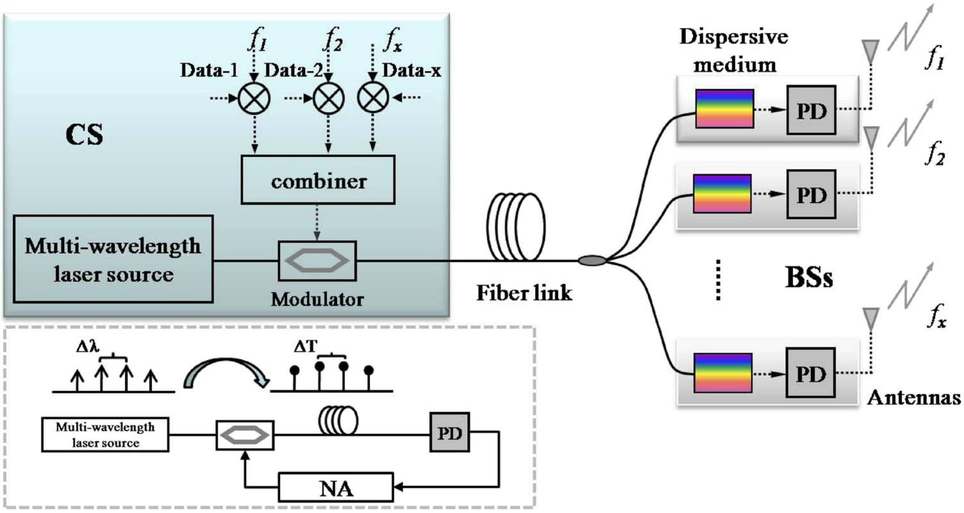


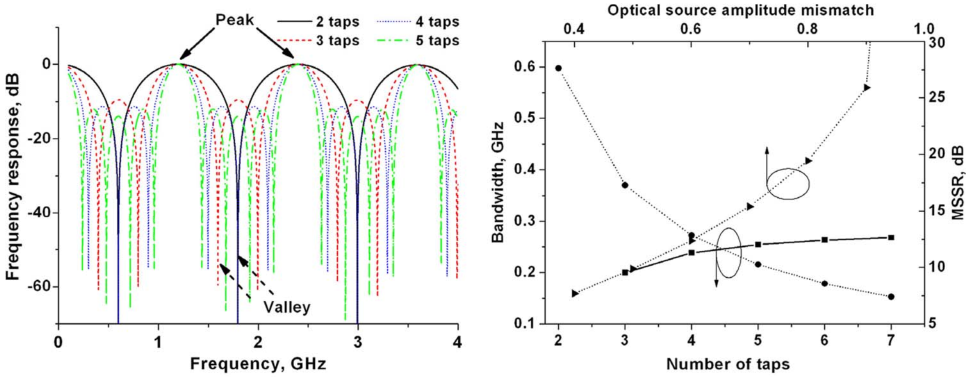
Fig. 1. Proposed system configuration subcarrier multiplexed RoF system with a multiple-optical-source-based microwave photonic filter.

RoF/mmW-over-fiber systems is the simplified and cost-effective RAUs, a simpler and cheaper demultiplexer is essential for the multiplexed RoF/mmW-over-fiber systems. In this way, the implementation of a demultiplexer in photonic method tends to be a desirable solution for a subcarrier multiplexed RoF/mmW-over-fiber system. Several methods have been reported [5], [6], in which either robust fiber Bragg grating with very narrow bandwidth or a complicated system configuration is needed.

In this paper, we report a novel and simple demultiplexing approach for the subcarrier multiplexed RoF system using a multiple-optical-source-based microwave photonic filter. The microwave photonic filter is embedded in the RoF system to perform as a demultiplexer, and the desired subcarrier frequency can be chosen by carefully controlling the sampling time between different taps of the filter. Subcarriers with different frequencies modulated with pseudo-random codes were demultiplexed separately in the experiment, and the system performance by using a two-optical-source-based microwave photonic filter performing as a demultiplexer was measured. In the proposed demultiplexing approach, the multiple optical sources shared by all the RAUs are placed in the CS, with only dispersive medium needed in each RAU, which is a cost-effective, easy to implement, tunable, and has good potential applications in subcarrier multiplexed RoF/mmW-over-fiber systems.

2. Operating Principle

The configuration of the proposed demultiplexing approach for subcarrier multiplexed RoF system employing multiple-optical-source-based microwave photonic filter is shown in Fig. 1. In the CS, a multiwavelength laser or laser diode array is used as the optical source. Different formats of the data streams are mixed with the RF subcarrier of different frequencies, i.e., $f_1, f_2, \ldots, f_x$, and are then modulating the optical source by an external modulator. The modulated optical signal is transmitted via the fiber link to the RAUs. In each RAU, different data with different subcarrier frequencies need to be demultiplexed for particular customers, and a dispersive medium with tailored delay characteristics is allocated before the modulated optical signal is recovered by the photo-detector (PD) and then radiated by the following antenna. The frequency of the subcarrier used and the time delay value of the dispersive medium in each RAU should be carefully designed to make the desirable frequency located at the peak and the undesired one at the valley of the transfer response. The architecture of the microwave photonic filter based on multiple optical sources is shown in the dashed block of Fig. 1. The lightwave from a multiwavelength source is modulated by microwave signal from Port 1 of the network analyzer (NA) and then sent to a



(a) (b)

Fig. 2. Frequency response of multiple optical source based microwave photonic filters with two taps (black solid line), three taps (red dotted line), four taps (black dotted line), and five taps (green dash dotted line) (a) and the relationship between bandwidth, MSSR, and the number of taps and optical source amplitude mismatch (b).

dispersive medium, where different wavelengths experienced different time delays. The different delayed taps are combined at the PD to recover the microwave signal, which is then sent to port 2 of the NA for testing.

One can see from Fig. 1 that the multiple-optical-source-based microwave photonic filter is embedded in the subcarrier multiplexed RoF system. By controlling the dispersive medium in each RAU, which changes the free spectrum range (FSR) of the microwave photonic filter, the subcarriers with different frequencies can be demultiplexed. Furthermore, if the dispersive medium could be tuned, then the subcarrier for radiation in each RAU could be switched between different frequencies, which would further enhance the flexibility of the multiplexed RoF system. Ignoring the linewidth of the optical source, the transfer function of the multiple-optical-source-based microwave photonic filter can be expressed as (1), shown below, where Ω is the RF frequency, λ is the central wavelength of the optical source, and P_n is the amplitude of the nth wavelength. D, L, and c are the dispersion parameter of the fiber coil, length of fiber, and the light velocity in the medium, respectively, [7]

$$H_{RF}(\Omega) = \cos\left(\frac{\pi\lambda^2\Omega^2 DL}{2c}\right)\left|\sum_{n=1}^{N} P_n \exp[-j\pi(n-1)\Omega DL\Delta\lambda]\right|. \tag{1}$$

The FSR of the microwave photonic filter is given by $FSR = 1/DL\Delta\lambda$, which should be carefully designed for the subcarrier de-multiplexing and band rejection. The number of the optical source is also an important parameter for the design of the microwave photonic filter. The frequency responses of the multiple-optical-source-based microwave photonic filter with different wavelengths (2 to 5) are shown in Fig. 2(a), with the same amplitude for every wavelength and even spacing. One can see that the microwave photonic filter with N optical sources will have N-2 sidelobes, and a microwave photonic filter with more taps has narrower passband bandwidth, which is shown as the solid circles in Fig. 2(b). The frequency response of the microwave photonic filter has periodic peaks and nonperiodic valleys, and by carefully designing the dispersive medium, the subcarrier with desirable frequency can be located at the peak of the filter, and the undesirable one can be placed at the valley frequency. It can also be seen that, as the number of taps increases, the filter's main to secondary sidelobe ratio (MSSR) increases slightly, which is shown as the solid rectangle in Fig. 2(b). The relative amplitude of optical sources also has influence on the frequency response of the microwave photonic filter. For the microwave photonic filter with two taps (a notch filter), the notch depth decreases when the amplitude difference between the two wavelengths increases, which is shown as the triangle in Fig. 2(b). In this way, the amplitudes of two optical sources should be made equal to get a larger notch depth.

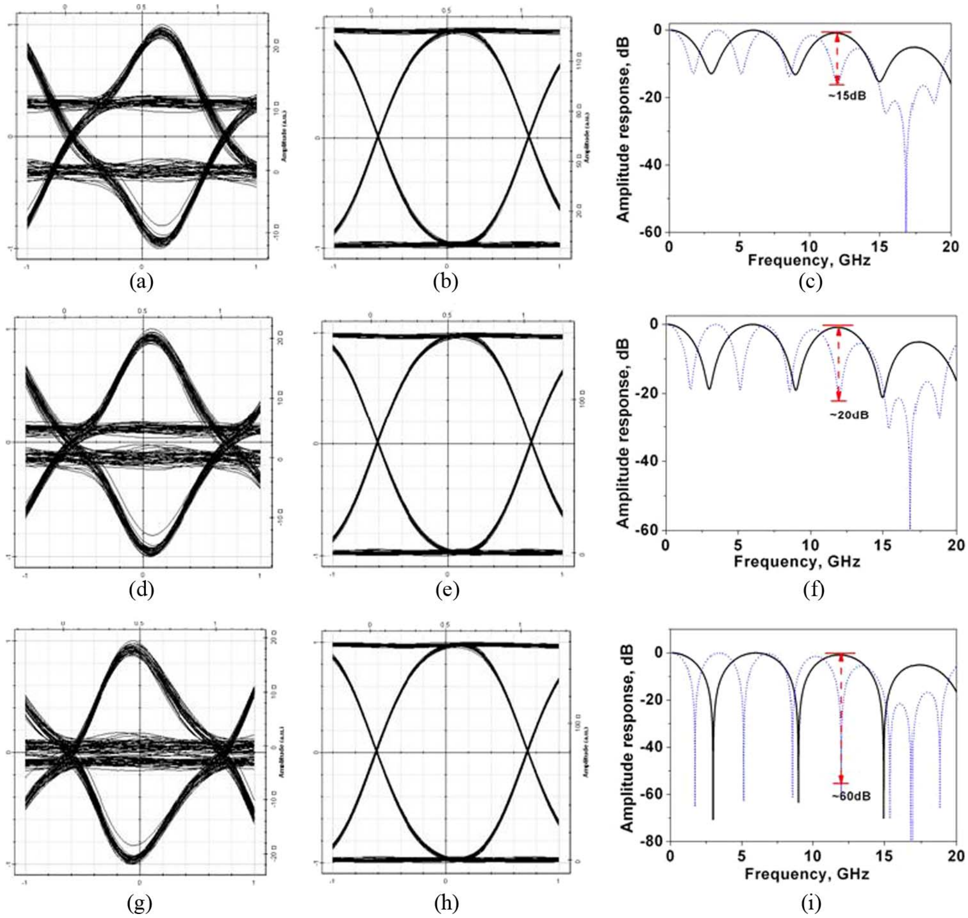


Fig. 3. Calculated results of the eye diagrams in BS1 (a), (d), (g), BS2 (b), (e), (h), and corresponding frequency response when the power ratio of two optical sources are 1 : 0.63 (a)–(c), 1 : 0.79 (d)–(f), and 1 : 1 (g)–(i), respectively.

The influence of the power mismatch of two optical sources on the system performance has been evaluated. In the simulation, two optical sources with the wavelength of 1551 nm and 1552 nm are used in the CS, and the length of fiber link between the CS and BS is 10 km. A length of 7.5 km SMF is placed in BS1 as a dispersive medium, while in BS2, there are no extra dispersive elements, and the signal from the CS is demultiplexed directly. In this case, if the frequency of the subcarrier is set to 12 GHz (modulated with 1 Gb/s NRZ data stream), it will be suppressed in BS1 since its located in the valley frequency, and in BS2, it is at the peak frequency, and therefore, the signal can be well demultiplexed. Fig. 3 shows the calculated results of the eye diagram in BS1, BS2, and the corresponding frequency response, when the power ratio of two optical sources are 1 : 0.63 (a)–(c), 1 : 0.79 (d)–(f), and 1 : 1 (g)–(i), respectively. One can see that, as power ratio of two optical sources gets closer to 1, the notch depth becomes larger, and in turn, the eye diagram of BS1 changes from open to close, while that of BS2 keeps widely open.

3. Experimental Demonstration

In the experiment, we implement a two-tap microwave photonic filter in an RoF system, and the experimental setup is shown in Fig. 4. A tunable laser (TL, Agilent 81940A) and a commercial distributed feedback (DFB) laser (Lightcomm OS-D-155) are used as the optical sources, which are combined by an optical coupler (OC). The optical carrier is launched to a Mach–Zehnder modulator (MZM) after a polarization controller (PC). The subcarrier from a microwave signal generator (MSG,

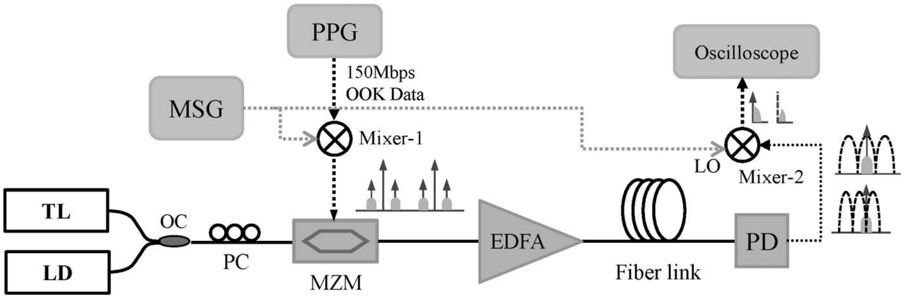
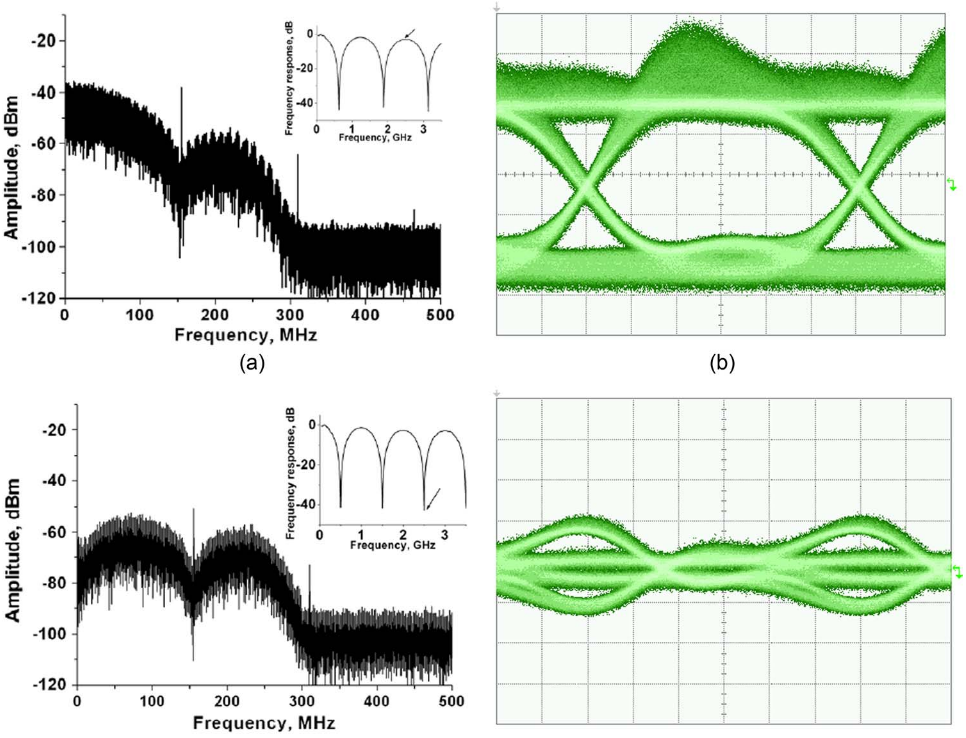


Fig. 4. Experiment setup for the RoF system embedded with two-tap-based microwave photonic filter.



(a) (b)

(c) (d)

Fig. 5. Measured baseband electrical spectra and eye diagram in the RAU when the subcarrier frequency located at the filter's transmission peak (a), (b) and located at the filter's notch point (c), (d).

Agilent E8257D) with the frequency of 2.5 GHz is mixed with the 150-Mb/s OOK data from a pseudo-pattern generator (PPG-SQA, Anritsu MP1800) and modulates the optical carrier via the MZM. Then, the modulated optical signal is amplified by an EDFA and transmitted through a 25-km fiber link. In the RAU, the microwave signal is recovered by a photodiode (PD) with 10-GHz bandwidth and then mixed with the local oscillator (LO) to get the baseband signal, which is then tested by the oscilloscope (Agilent 86100A).

By employing the embedded microwave photonic filter, the desired signal located at the peak frequency of the filter is filtered out, and the undesirable signal located at the valley frequency is suppressed. In the experiment, we do not employ the tunable dispersive medium in the RAU; instead, a tunable laser is used. By changing the wavelength spacing of the two optical sources, the time delay between the two taps of the filter can be tuned consequently. When the wavelengths of the TL and LD are 1552.89 nm and 1554.75 nm, respectively, the FSR of the embedded microwave photonic filter is estimated to be 1.265 GHz $(D = 17\ \text{ps/nm/km})$, and the microwave subcarrier is located at the peak of the filter's response. The baseband electrical spectrum after mixer-2 and the eye diagram of the system are shown as Fig. 5(a) and (b), respectively. The frequency response is shown in the inset of Fig. 5(a). It shows that the eye diagram is clearly open, and the information is recovered well, since the microwave subcarrier is located at the filter's peak, and the 620-MHz 3-dB bandwidth of the microwave photonic filter is much larger than the data bandwidth. When the wavelength of TL is tuned to 1552.4 nm, the filter's FSR is shown to be 1.02 GHz, and the frequency of the microwave subcarrier is located at the filter's notch. The baseband electrical spectrum after mixer-2 and the eye diagram of the system are shown as Fig. 5(c) and (d), respectively. The frequency response is shown in the inset of Fig. 5(c). To get a deeper notch, the amplitudes of the TL and LD are set the same, which in our experiment is about 0 dBm, and a 40-dB notch depth of the embedded filter is achieved. Since the microwave subcarrier with the modulated data is suppressed, the information can no longer be recovered in the RAU, which results in a closed eye diagram for the transmission system.

4. Conclusion

In this paper, the multiple-optical-source-based microwave photonic filter is integrated into a subcarrier multiplexed RoF system to perform as a demultiplexer. The peaks of the filter's frequency response can be used to get the desired subcarrier, and valleys of the filter can be utilized to suppress undesirable subcarrier frequency. Since the multiple-optical-source-based microwave photonic filter has periodic transmission peaks and non-periodic valleys, the filter's parameters, such as the time delay and the relative amplitude between different taps, need to be carefully designed to demultiplex the subcarrier in this multiplexed RoF system. The system performance by using a microwave photonic filter with two optical sources as a demultiplexer has been measured in our experiment and verified that the microwave photonic filter integrated in the RoF system works well as the demultiplexer. To our best knowledge, it is the first time that a microwave photonic filter has been implemented in an RoF system as a demultiplexer and that the system performance has been evaluated. Due to its cost-effectiveness and flexibility, this approach will have good application potentials in the next-generation subcarrier multiplexed RoF systems.

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