



Scalable and reconfigurable generation of flat optical comb for WDM-based next-generation broadband optical access networks

Chen Chen^{a,b}, Chongfu Zhang^{a,c,*}, Wei Zhang^a, Wei Jin^a, Kun Qiu^a

^a Key Lab of Optical Fiber Sensing and Communication Networks (Ministry of Education), and School of Communication and Information Engineering, University of Electronic Science and Technology of China, Chengdu, Sichuan 611731, China

^b School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore

^c Department of Electrical Engineering, University of Southern California, Los Angeles, CA 90089, USA

ARTICLE INFO

Article history:

Received 20 June 2013

Received in revised form

11 January 2014

Accepted 23 January 2014

Available online 5 February 2014

Keywords:

Tunable comb generator

Broadband optical access network

Wavelength-division multiplexing

Radio-over-fiber

Passive optical network

Orthogonal frequency-division multiple access

ABSTRACT

A tunable comb generator (TCG) by cascading a single phase modulator (PM) with two identical intensity modulators (IMs) is proposed for the scalable and reconfigurable generation of flat optical comb. Detailed theoretical analysis is performed to find out the optimized condition for flat optical comb generation using the proposed TCG and the scalability of the generated optical comb is also analyzed under the optimized condition. An experiment is conducted to verify the feasibility of the TCG and the experimental results agree well with the theoretical prediction. The reconfigurability and stability of the obtained optical comb are discussed as well in the experiment. After that, the obtained optical comb is utilized as the optical source for a wavelength-division multiplexed radio-over-fiber (WDM-RoF) system and a hybrid WDM orthogonal frequency-division multiple access passive optical network (WDM-OFDMA-PON). Two corresponding experimental demonstrations are presented to verify the feasibility of employing the obtained flat optical comb as the WDM optical source, respectively. In the WDM-RoF system, 17 WDM channels each carrying 16×5 Gb/s non-return-to-zero (NRZ) data have been up-converted to 10 GHz simultaneously. In the hybrid WDM-OFDMA-PON, 17-channel OFDM-WDM double-sideband (DSB) signal achieving 10.85 Gb/s traffic per channel is successfully transmitted for both wired baseband OFDM access and wireless 10 GHz OFDM access.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

In order to better exploit the enormous bandwidth of optical fiber and to further increase the system capacity, wavelength-division multiplexing (WDM) reveals significant potential for the application in next-generation broadband optical access networks (NG-BOANs) [1,2]. In a typical WDM-based BOAN system, such as a WDM-based radio-over-fiber (WDM-RoF) system or a WDM-based passive optical network (WDM-PON), a bank of cost-sensitive independent lasers are often employed as the WDM optical source to provide multiple WDM channels [2,3]. A well-developed WDM system should satisfy the following requirements: (1) scalability which means the number of WDM channels should be tunable according to the number of connected end users; (2) reconfigurability which indicates that frequency spacing of the WDM channels should be adjustable considering the channel crosstalk effects; (3) flatness of the channel output power level and (4) easy control of the stability of all the WDM channels, including high

frequency accuracy and uniform precise channel spacing [4–6]. However, in the WDM system that multiple independent lasers are used to form the WDM channels, the overall cost increases when a large number of lasers are used. Also, the number of WDM channels is limited due to the difficulty of managing tens or hundreds of independent lasers which is too complicated and inevitably reduces the scalability and reconfigurability of the WDM system. Furthermore, effective control of the absolute frequencies and the channel spacing becomes scarcely possible when a large number of independent lasers are utilized and thus the stability of the WDM system can hardly be guaranteed [5].

The optical comb source, which is also named as multi-carrier or multi-wavelength source, is a promising candidate to serve as the WDM optical source [5,6]. An optical comb source with multiple comb lines can provide as many WDM channels, so employing such an optical comb in the WDM system can greatly reduce the number of independent lasers and simplify the stability controlling process. Extensive investigations about the generation of optical comb have been reported in the past for a long time. Many comb generation approaches have been proposed such as using an amplified fiber loop with injection locked oscillators [7], involving fiber nonlinearity like four-wave mixing (FWM) [8] or directly modulating a laser diode [6,9]. Nevertheless, most of these methods are either complicated or not easily applicable in WDM

* Corresponding author at: Key Lab of Optical Fiber Sensing and Communication Networks (Ministry of Education), and School of Communication and Information Engineering, University of Electronic Science and Technology of China, Chengdu, Sichuan 611731, China.

E-mail address: cfzhang@uestc.edu.cn (C. Zhang).

systems because the generated optical comb lacks of scalability, reconfigurability, flatness or stability. Optical modulation is another interesting approach to generate an optical comb and it has already been widely studied. In general, optical modulation based comb generation can be divided into two categories: (1) using a single optical modulation format, such as phase modulation [10,11], intensity modulation [12–14] or polarization modulation [15]; and (2) using a combination of different modulation formats, such as hybrid phase and intensity modulation by cascading phase modulators (PMs) with intensity modulators (IMs) [4,16–20]. To sum up, in the hybrid phase and intensity modulation based comb generation approach, the PM is used to generate many comb lines over a wide frequency range which improves the scalability of the generated optical comb, while the IM is used to flatten the spectrum of the generated comb by properly adjusting the DC bias voltage of the IM. Consequently, the hybrid phase and intensity modulation is a quite attractive way for the generation of the optical comb source with enhanced scalability and flatness. Meanwhile, reconfigurability of the optical comb source can be achieved by using frequency-tunable radio frequency (RF) sources to flexibly adjust the comb line spacing and stability of the optical comb source can also be guaranteed by employing DC bias controllers for the IMs. So far, most of the literatures have just focused on improving the flatness of the optical comb, while the scalability, reconfigurability and stability of the obtained optical comb have not been thoroughly investigated [4,16–20].

In this paper, we for the first time propose a tunable comb generator (TCG) to efficiently generate the optical comb source with enhanced scalability, reconfigurability, flatness and stability, by cascading a single PM with two identical IMs. The generated optical comb source is then utilized as the WDM optical source for a WDM-RoF system and a hybrid orthogonal frequency-division multiple access based WDM-PON (WDM-OFDMA-PON). This paper is organized as follows. In Section 2, theoretical analysis of the mathematical generation of the optical comb source using the proposed TCG is firstly presented. The optimized condition for the generation of a flat optical comb is achieved according to the mathematical derivation and the corresponding flatness and scalability are analyzed under the optimized condition. After that, a detailed experiment is conducted to verify the feasibility of the proposed TCG. Experimental results agree well with the theoretical prediction about the flatness and scalability of the obtained optical comb. Meanwhile, the reconfigurability and stability of the obtained optical comb are also discussed in this part. Experimental demonstrations of a WDM-RoF system and a hybrid WDM-OFDMA-PON utilizing the obtained optical comb source are presented in Sections 3 and 4, respectively. In Section 3, 17 WDM channels each carrying 16×5 Gb/s non-return-to-zero (NRZ) data have been simultaneously up-converted to 10 GHz in the WDM-RoF system. An average receiver (Rx) sensitivity for all 17 WDM channels at a bit-error-rate (BER) of 10^{-9} after 25 km standard single mode fiber (SSMF) is about -18.5 dBm. In Section 4, 17-channel OFDM-WDM-DSB signal achieving 10.85 Gb/s traffic per channel is generated for both wired baseband OFDM access and wireless 10 GHz OFDM access. A power penalty of about 1.3 dB has been observed for the wired and the wireless access in the hybrid WDM-OFDMA-PON.

2. Scalable and reconfigurable generation of flat optical comb

2.1. Theoretical analysis

Fig. 1 illustrates the principle of the proposed TCG for the scalable and reconfigurable generation of flat optical comb. It

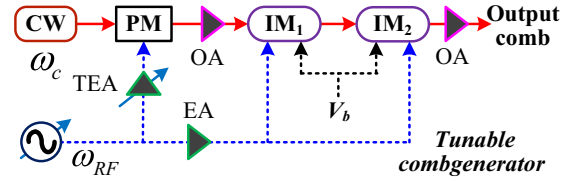


Fig. 1. Principle of the proposed TCG for scalable and reconfigurable generation of flat optical comb.

contains a continuous-wave (CW) laser, a frequency-tunable sinusoidal RF source, a single PM and two identical IMs. In addition, a tunable electrical amplifier (TEA) is employed to control the input peak-to-peak voltage (PPV) of PM driven signal so as to dynamically control the scalability of the obtained comb [19], while another electrical amplifier (EA) is used to boost the input PPV of IM driven signal to an optimized level. Two optical amplifiers (OAs) are utilized to control the output optical power of the generated comb. By tuning the frequency of the RF source, the reconfigurability of the obtained comb can be successfully achieved. By optimizing the parameters of the TCG, an optical comb with excellent flatness can be obtained. Therefore, the tunability of the proposed TCG enables the scalability and reconfigurability of the obtained flat optical comb. In the proposed TCG, two identical IMs are employed. We assume that these two IMs are driven by the same RF signal and also biased at the same DC voltage, so only one EA is required to boost the PPV of their driven signal and only one DC bias controller is needed to guarantee a stable DC bias voltage for these two IMs. Compared with the case that two IMs have different RF driven signals and different DC bias voltages, the overall complexity and cost of the proposed TCG to generate a stable optical comb can be relatively reduced. Considering that two IMs have the same optimized DC bias voltages and only one single DC bias controller is used, the overall complexity and cost to guarantee the stability of the optical comb generated by our proposed TCG are exactly the same with the case that only one PM and one IM are cascaded [17–19].

In order to study the flatness of the optical comb generated by the proposed TCG, we have theoretically analyzed the mathematical generation of the optical comb [21]. The optical field of the CW laser can be given by

$$E_c(t) = E_c \exp(j\omega_c t) \quad (1)$$

where E_c and ω_c are the amplitude and the angular frequency terms, respectively. We define the PM driven signal as $V_{PM}(t) = V_{PM} \cos(\omega_{RF} t)$ where V_{PM} is the PPV after being boosted by the TEA and ω_{RF} is the angular frequency of the RF source. In this scheme, we assume that two identical IMs are driven by the same RF signal, so we can define their driven signal as $V_{IM}(t) = V_{IM} \cos(\omega_{RF} t)$ where V_{IM} is the PPV after being boosted by the EA. The DC bias voltages of IM₁ and IM₂ are assumed to be the same which can be expressed as V_b . Half-wave voltages of the PM and two IMs can be given as $V_{\pi PM}$ and $V_{\pi IM}$, respectively. The modulation index of the PM is defined as m_{PM} and the modulation index of two IMs is defined as m_{IM} , while the normalized DC voltage of two IMs is defined as β . Thus, m_{PM} , m_{IM} and β can be expressed as

$$m_{PM} = \frac{V_{PM}}{V_{\pi PM}}, \quad m_{IM} = \frac{V_{IM}}{V_{\pi IM}}, \quad \beta = \frac{V_b}{V_{\pi IM}}. \quad (2)$$

The optical fields at the outputs of the PM, IM₁ and IM₂ can be respectively given as follows

$$E_{PM}(t) = E_c \exp(j\omega_c t) \exp[j\pi \times m_{PM} \cos(\omega_{RF} t)] \quad (3)$$

$$E_{IM_1}(t) = \frac{E_c}{2} \exp(j\omega_c t) \{ \exp[j\pi \times m_{PM} \cos(\omega_{RF} t)] + \exp(j\beta) \exp[j\pi \times (m_{PM} + m_{IM}) \cos(\omega_{RF} t)] \} \quad (4)$$

$$E_{IM_2}(t) = \frac{E_c}{4} \exp(j\omega_c t) \{ \exp[j\pi \times m_{PM} \cos(\omega_{RF} t)] + 2\exp(j\beta) \exp[j\pi \times (m_{PM} + m_{IM}) \cos(\omega_{RF} t)] + \exp(j2\beta) \exp[j\pi \times (m_{PM} + 2m_{IM}) \cos(\omega_{RF} t)] \}. \quad (5)$$

Using the Bessel functions, the optical field at the output of IM_2 , which is also the output optical field of the optical comb generated by the proposed TCG, can be expanded as

$$E_{IM_2}(t) = \frac{E_c}{4} \sum_{n=-\infty}^{\infty} J_n(\pi \times m_{PM}) + 2\exp(j\beta) J_n[\pi \times (m_{PM} + m_{IM})] + \exp(j2\beta) J_n[\pi \times (m_{PM} + 2m_{IM})] \times j^n \exp[j(\omega_c + n\omega_{RF})t] \quad (6)$$

where n is the comb line index. According to (6), the obtained optical comb can be expanded as many individual comb lines and the frequency of the n th comb line is $\omega_c + n\omega_{RF}$. Therefore, the normalized peak power (NPP) of the n th comb line of the obtained optical comb can be described as

$$NPP(n) = \frac{1}{16} \left| \frac{E_c \times \{J_n(\pi \times m_{PM}) + 2\exp(j\beta) J_n[\pi \times (m_{PM} + m_{IM})] + \exp(j2\beta) J_n[\pi \times (m_{PM} + 2m_{IM})]\}}{j^n} \right|^2 \quad (7)$$

where $J_n(x)$ is the first kind Bessel function of order n . For an obtained optical comb with m comb lines for use, the flatness of this comb can be defined as

$$Flatness(m) = \max[NPP(m)] - \min[NPP(m)] \quad (8)$$

where $\max[NPP(m)]$ and $\min[NPP(m)]$ are the maximum NPP and

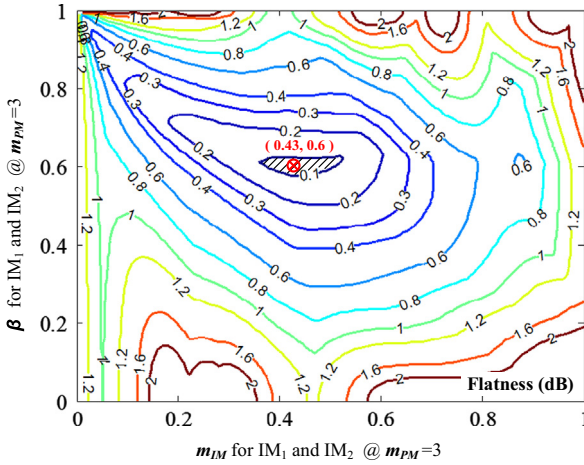


Fig. 2. Calculated comb flatness versus the modulation index and the normalized DC bias voltage of two IMs for seventeen comb lines.

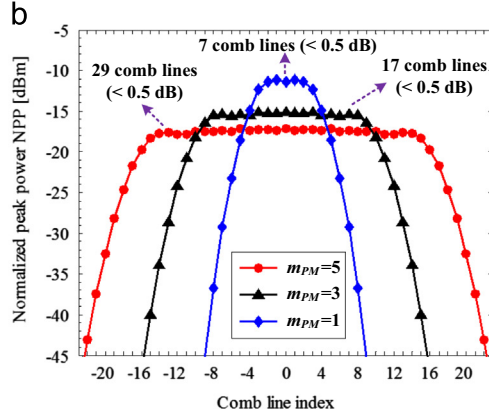
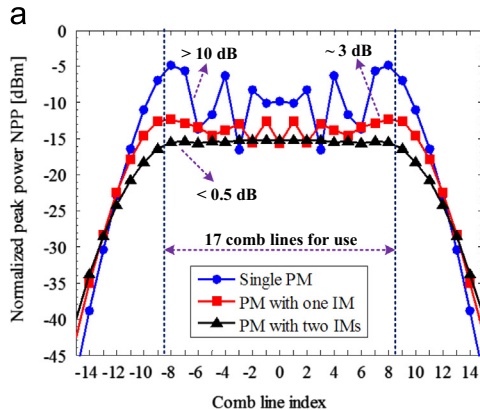


Fig. 3. (a) Normalized peak power NPP versus comb line index for three different cases: (1) single PM, (2) PM with one IM and (3) PM with two IMs. (b) Normalized peak power NPP versus comb line index for different PM modulation indices: (1) $m_{PM}=5$, (2) $m_{PM}=3$ and (3) $m_{PM}=1$.

the minimum NPP of this comb with m comb lines for use, respectively.

Fig. 2 shows the calculated comb flatness with the relationship of the modulation index (X-axis) and the normalized DC voltage (Y-axis) of two IMs, in which the Z-axis gives the flatness for 17 comb lines. In Fig. 2, modulation index of the PM is set to 3 and thus 17 comb lines in the obtained comb are for use. As can be seen from Fig. 2, the central shaded area represents a flatness of 0.1 dB and the red cross point (0.43, 0.6) in this area indicates one of the optimized conditions for the modulation index and the normalized DC voltages of two IMs. In our following experimental demonstrations, this condition (the modulation index and the normalized DC voltage of two IMs are 0.43 and 0.6, respectively) is adopted to optimize the corresponding parameters so as to obtain a flat optical comb.

In our proposed TCG, three optical modulators including a single PM and two identical IMs are cascaded to generate an optical comb with excellent flatness. Compared with the schemes that only one PM or a pair of PM and IM are utilized, the flatness of the obtained optical comb generated by the TCG is further improved by optimizing the DC bias voltages of two identical IMs and it can be held in 0.1 dB according to Fig. 2. The relationship between the NPP and the comb line index for three different cases is given in Fig. 3(a). For the first case that only a single PM is used, the flatness for 17 comb lines is more than 10 dB while a flatness of about 3 dB for 17 comb lines has been observed for the second case that a single PM and a single IM are used. For the third case that a single PM is cascaded with two identical IMs, which is adopted in our proposed TCG, the flatness for 17 comb lines is less than 0.5 dB (about 0.1 dB). In consequence, the flatness of the obtained optical comb can be greatly improved when two IMs are cascaded after the PM. The relationship between the NPP and the comb line index for different PM modulation index is described in Fig. 3(b). When the PM modulation index is set at 1, only 7 comb lines are held in the flatness less than 0.5 dB. The comb line amount within 0.5 dB flatness increased to 17 and 29 when the PM modulation index is set at 3 and 5, respectively. It can be seen that the comb line count grows significantly when the PM modulation index is increased. Therefore, the obtained optical comb generated by the proposed TCG has a fine scalability which can be accurately adjusted by dynamically control the PM modulation index of the TCG.

2.2. Experimental verification

The experimental setup of the proposed TCG is shown in Fig. 4. A distributed-feedback (DFB) laser at 1552.52 nm is used as the optical CW source of the TCG and a polarization controller (PC) is

followed to control the laser output power and adjust its polarization state. A LiNbO₃ PM with a half-wave voltage of 3.2 V and two single-arm chirp-free LiNbO₃ IMs with both half-wave voltages of 4.6 V are cascaded in the TCG. The modulation bandwidths of the PM and two IMs used in the experiment are all 20 GHz. A short period of polarization maintaining fiber (PMF) has been used between the PM and IMs to maintain the polarization state of the signal. In this experiment, two IMs are chosen of the same type to guarantee that they are identical and they are also driven by the same RF signal which is amplified by the EA. The same DC bias voltages are applied to these two IMs and thus only a single DC bias controller is required in the proposed TCG to maintain a stable output optical comb. A frequency-tunable RF source is employed to drive the cascaded PM and two IMs, while a phase shifter (PS) is adopted to compensate for the phase delay between the driven signals of the PM and two IMs. As can be known that the use of two cascaded IMs inevitably brings high insertion loss (IL), two erbium doped fiber amplifiers (EDFAs) are employed before and after these two IMs to compensate for the IL and improve the optical power of the obtained comb to a proper level.

The input PPV of PM driven signal is boosted by an EA with gain control, which is used as the TEA to dynamically control the modulation index of the PM so as to generate a scalable optical comb. In order to obtain a flat optical comb, the optimized condition for the modulation index and the normalized DC voltages of two IMs calculated from Fig. 2 is adopted in our experiment. According to the optimized condition, the modulation index of two IMs is set to 0.43 by controlling the input PPV of their

driven signals to 1.98 V while the normalized DC voltages are both set to 0.6 by controlling their DC bias voltages to 2.76 V. It is worth noting that these two parameters of two IMs are fixed during the whole experiment so as to guarantee the flatness of the obtained optical comb. In order to obtain a scalable and reconfigurable optical comb, the PPV of PM driven signal and the frequency of the RF source in the TCG need to be dynamically adjusted according to the requirements of scalability and reconfigurability.

Fig. 5 shows the optical spectra of the obtained comb generated by the proposed TCG. The theoretically calculated optical spectrum is expressed in Fig. 5(a) for reference. It is clear that totally 17 comb lines held in the flatness less than 0.5 dB (about 0.1 dB) can be obtained under the optimized condition when the PM modulation index is set to 3. The corresponding experimental optical spectra with 10 GHz spacing ($f_{RF}=10$ GHz) and 30 GHz spacing ($f_{RF}=30$ GHz) are illustrated in Fig. 5(b) and (c), respectively. The flatness achieved by experiment under the optimized condition is about 0.5 dB which is degraded by 0.4 dB compared with the theoretical prediction in Fig. 2. We believe that this small deterioration in flatness is mainly caused by the intrinsic difference of two IMs where we assume two identical IMs to be used in the theoretical analysis. Fig. 5(d) gives the experimental optical spectrum of the obtained comb when the PM modulation index is set to 5 and the spacing is 30 GHz ($f_{RF}=30$ GHz). There are 29 comb lines generated held in the flatness about 0.5 dB and it proves the scalability of the obtained comb generated by the proposed TCG. Moreover, by comparing Fig. 5(b) with Fig. 5(c) and (d), we can find out that by tuning the frequency of the RF source, the frequency spacing of two adjacent two comb lines is reconfigurable.

We further analyze the scalability of the generated optical comb by setting the PM modulation index of the TCG to various values and the relationship between the comb line amount and the PM modulation index is depicted in Fig. 6. It can be seen that the comb line amount has a direct proportion relationship with the PM modulation index which indicates that scalability of the generated optical comb can be flexibly adjusted by dynamic control of the PM modulation index. In order to enhance the scalability of the optical comb generated by the TCG, a PM with

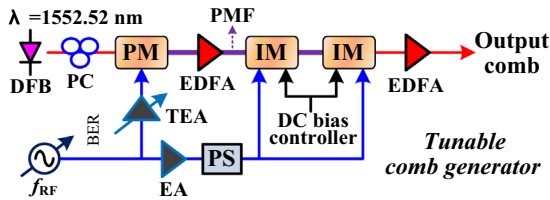


Fig. 4. Experimental setup of the proposed TCG.

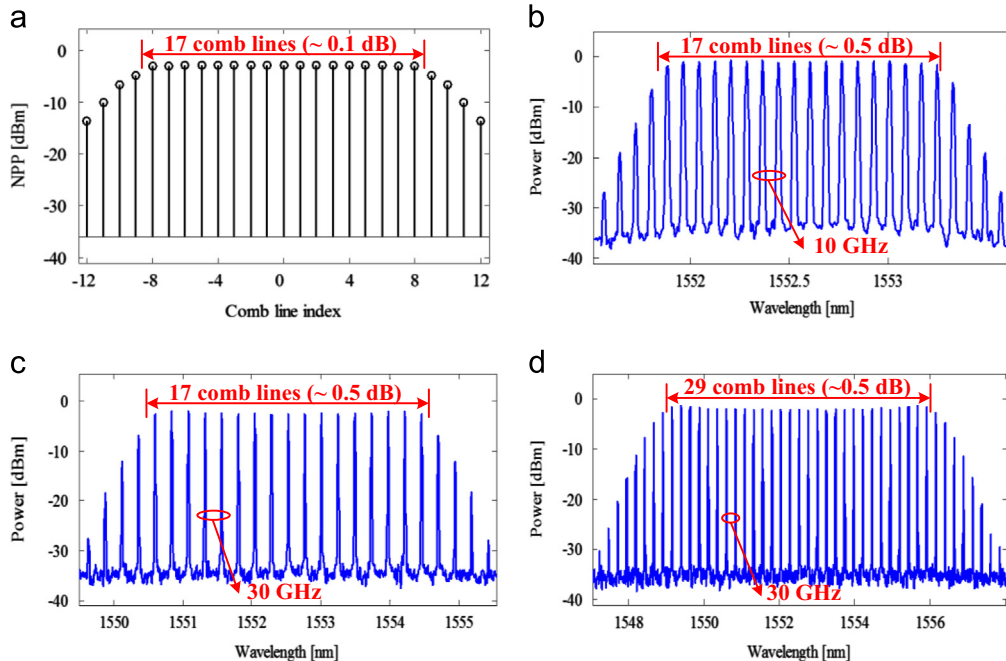


Fig. 5. Optical spectra of the obtained comb flatness generated by the proposed TCG: (a) $m_{PM}=3$ by theory, (b) $m_{PM}=3$ with 10 GHz spacing by experiment, (c) $m_{PM}=3$ with 30 GHz spacing by experiment and (d) $m_{PM}=5$ with 30 GHz spacing by experiment.

relatively low half-wave voltage or two cascaded PMs can be used to obtain more comb lines within the flatness window [18].

3. Simultaneous up-conversion for WDM-RoF systems using the proposed TCG

The experimental setup of simultaneous up-conversion for WDM-RoF systems using the proposed TCG is shown in Fig. 7. In the central station (CS), the proposed TCG is utilized to generate a flat optical comb with excellent scalability and reconfigurability. In the TCG, the wavelength of the DFB laser and the frequency of the RF source are 1552.52 nm and 30 GHz, respectively. The PM modulation index is set to 3 while the optimized condition about the modulation index and the normalized DC voltages of two IMs are guaranteed, so an optical comb with totally 17 comb lines held in 0.5 dB flatness is obtained.

The obtained flat optical comb with 17 comb lines for use is then utilized as the optical source of the WDM-RoF system. An optical band-pass filter (BPF) with the central frequency of 1552.52 nm and a bandwidth of 4 nm is used to remove the unwanted high-order comb lines. After that, a coherent WDM source with 17 channels has been achieved. After passing a PC, the 17-channel comb is sent into another IM which is biased at its minimum transmission point to perform the optical carrier

suppressed DSB (OCS-DSB) modulation. The generated WDM-OCS-DSB signal is amplified by an EDFA before it is launched into the 25 km SSF.

In this proof-of-concept experiment, a broadcast structure is adopted for the proposed WDM-RoF system to verify the feasibility of employing the obtained flat optical comb as its optical source. Actually, an arrayed waveguide grating (AWG) can be used to separate all the comb lines and each comb line can be modulated with different data so as to form multiple unicast WDM channels. Because of the inadequate experimental facilities in our lab, we adopt a broadcast structure in the experiment just for the simplicity. In fact, for a practical WDM-RoF system, each channel may carry different data and the accompanying channel crosstalk effects would worsen the system performance. However, the accompanying channel crosstalk can be effectively mitigated when the channel spacing is kept large enough. In this experimental demonstration, the spacing of the 17-channel comb is 30 GHz. The spacing of two first-order sidebands of the OCS-DSB signal in each channel is 10 GHz since a 5 GHz RF source is used to up-convert the baseband NRZ data. Therefore, a spacing of 20 GHz is maintained between the two adjacent first-order sidebands of the OCS-DSB signals in two neighboring channels, which is large enough to mitigate the channel crosstalk to an acceptable level. Based on the discussion above, the experimental setup in Fig. 7 can be used to verify the feasibility of the application of the obtained flat optical comb in WDM-RoF systems. Nevertheless, channel crosstalk mitigation in the WDM-RoF system is an interesting topic which will be further studied in our following investigations.

In the CS, 5 Gb/s NRZ data with a PRBS length of $2^{31} - 1$ is firstly mixed with a 5 GHz RF source and then the mixed signal is utilized to drive the IM. Fig. 7(a) shows the obtained optical spectrum after OCS-DSB modulation and we can see that a 17-channel WDM-OCS-DSB signal has been generated. After 25 km SSF, the WDM-OCS-DSB signal is divided into 17 individual channels by an AWG with 30 GHz bandwidth and 5 dB loss in each output port. For the first channel (CH_1) of -6.4 dBm OCS-DSB signal, a variable optical attenuator (VOA) with 12 dB attenuation is used to emulate a 1:16 optical splitter. In consequence, totally $17 \times 16 = 272$ base stations (BSs) can be supported in our experiment. Received optical spectrum of OCS-DSB signal in CH_1 at BS_{1-k} is given in Fig. 7 (b) and we can find out that the signal-to-carrier ratio (SCR) of the received OCS-DSB signal is 15 dB while the signal-to-noise ratio (SNR) is 26 dB. The received OCS-DSB signal is detected by a photodiode (PD) and then down-converted to baseband for BER

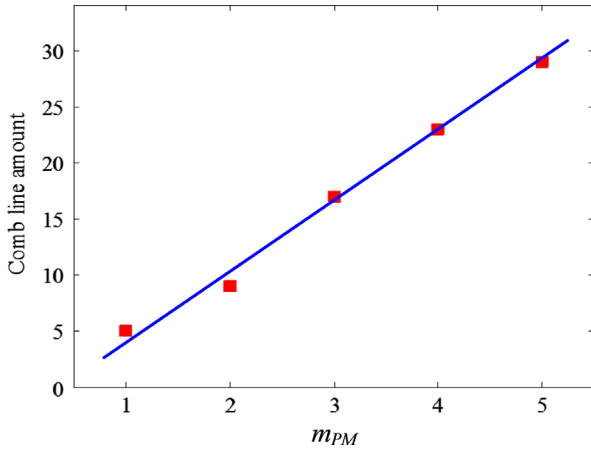


Fig. 6. Comb line amount with 0.5 dB flatness versus the PM modulation index.

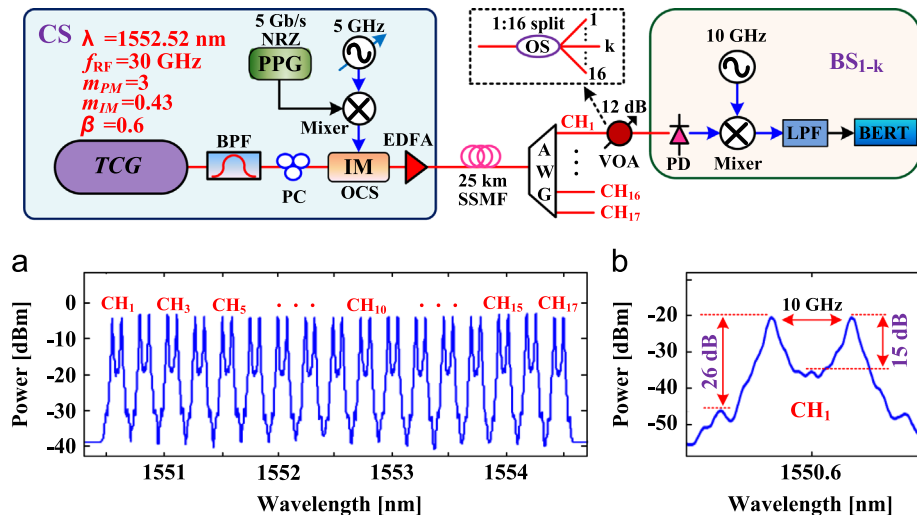


Fig. 7. Experimental setup of the simultaneous up-conversion for WDM-RoF systems using the proposed TCG. (a) Optical spectrum after OCS modulation and (b) Received optical spectrum of the first channel at BS_{1-k} .

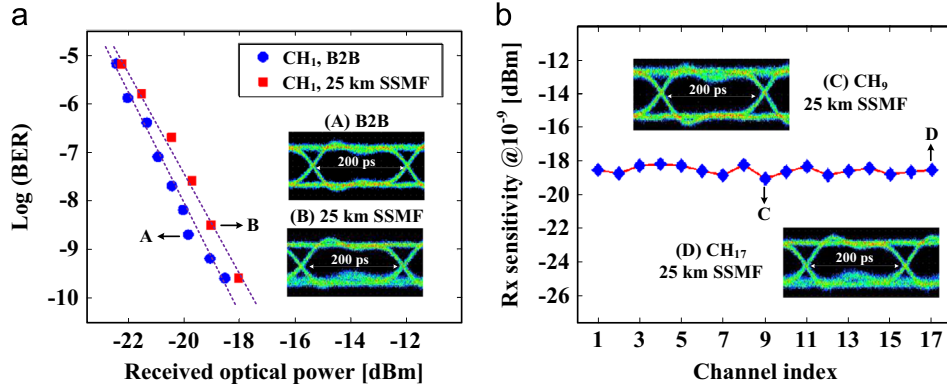


Fig. 8. Experimental results: (a) measured BER performance of CH₁ at BS_{1-k} for B2B and 25 km SSMF transmission and the corresponding eye diagrams; (b) receiver sensitivity of all seventeen channels for 25 km SSMF transmission and the corresponding eye diagrams for CH₉ and CH₁₇.

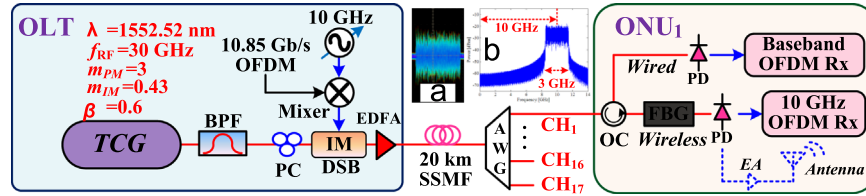


Fig. 9. Experimental setup of the hybrid WDM-OFDMA-PON using the proposed TCG. (a) Waveform and (b) electrical spectrum of the input OFDM signal.

test by mixing it with a 10 GHz RF source and passing an electrical low-pass filter (LPF). In a practical WDM-RoF system, the generated 10 GHz RF signal in the BS will be radiated by the antenna for wireless transmission. However, owing to the inadequate experimental facilities in our lab, the RF wireless transmission experiment is temporarily unfulfillable, so we just focus on the optical wired transmission of the WDM-RoF system. Compared with the practical WDM-RoF system with both RF wireless and optical wired transmission, the results obtained in this experiment might be relatively optimistic.

In order to evaluate the performance of the WDM-RoF system utilizing the proposed TCG, we firstly investigate the BER performance of CH₁ for back-to-back (B2B) and 25 km SSMF transmission. Then, we discuss the average receiver (Rx) sensitivity for all 17 channels at a BER of 10^{-9} after 25 km SSMF. Fig. 8(a) shows the measured BER performance for CH₁ at BS_{1-k} and the corresponding eye diagrams. As can be seen from Fig. 8(a), the optical powers to reach a BER of 10^{-9} for B2B and 25 km SSMF transmission are -19.2 dBm and -18.6 dBm, respectively. Therefore, the power penalty at the BER of 10^{-9} for B2B and 25 km SSMF is 0.6 dB. The eye diagrams for CH₁ at BS_{1-k} after B2B and 25 km SSMF transmission have also been inserted in Fig. 8(a) for further clarity. The Rx sensitivity at a BER of 10^{-9} after 25 km SSMF for all 17 channels is given in Fig. 8(b). The average Rx sensitivity is about -18.5 dBm. Eye diagrams for CH₉ and CH₁₇ after 25 km SSMF transmission are also inserted in Fig. 8(b). Downstream transmission of the WDM-RoF system employing the obtained flat optical comb has been demonstrated in our experiment and its feasibility has also been successfully verified. The colorless upstream transmission can also be realized by using reflective modulators so as to achieve a general bi-directional communication [22,23].

4. Hybrid WDM-OFDMA-PON using the proposed TCG

Fig. 9 illustrates the experimental setup of the hybrid WDM-OFDMA-PON for both wired and wireless access using the proposed TCG. In the optical line terminal (OLT), a scalable and

reconfigurable optical comb with 0.5 dB flatness is generated by the proposed TCG. All the parameters of proposed TCG are set exactly the same with that in Fig. 7 and thus the obtained flat optical comb with 17 comb lines held in 0.5 dB flatness is used as the optical source for the proposed hybrid WDM-OFDMA-PON. In this experiment, a uni-directional broadcast structure is also adopted to verify the feasibility of employing the obtained flat optical comb as its optical source. According to the corresponding discussions in Section 3, this simplification has no substantial influence on feasibility verification of the application of optical comb in the proposed hybrid WDM-OFDMA-PON.

The obtained optical comb with 17 comb lines held in 0.5 dB flatness also passes an optical BPF to remove the unwanted high-order comb lines. After passing a PC, the 17-channel comb is modulated with 10.85 Gb/s RF OFDM signal in an IM where a normal DSB modulation is performed. The baseband 16 QAM OFDM signal achieving 10.85 Gb/s traffic data with 3 GHz bandwidth is generated off-line with 128 subcarriers and a cyclic prefix (CP) of 1/32. After being uploaded into a Tektronix arbitrary waveform generator (AWG7102) at 10 Gsample/s, the baseband 16 QAM OFDM signal as shown in inset (a) of Fig. 9 is up-converted to 10 GHz by mixing with a 10 GHz RF source. The electrical spectrum of the generated 10 GHz OFDM signal is given in inset (b) of Fig. 9 and then it is modulated onto the optical comb to generate the 17-channel OFDM-WDM-DSB signal. The generated 17-channel OFDM-WDM-DSB signal is amplified by an EDFA before it is launched into the 20 km SSMF.

After 20 km SSMF, an AWG with the same parameters in Fig. 7 is utilized to divide the OFDM-WDM-DSB signal into 17 individual channels. For the CH₁, the left first-order sideband of the OFDM-DSB signal is reflected by a fiber Bragg grating (FBG) and then sent into a PD for wired baseband OFDM reception after an optical circulator (OC), while the transmitted OFDM-SSB signal is sent into another PD. As shown in dashed line, wireless OFDM signal is amplified by an electrical amplifier (EA) and then transmitted into the air via an antenna in practical situations. In our experiment, we just evaluate the performance of the received optical OFDM signal. In the OFDM Rx, the received 10 GHz OFDM signal is

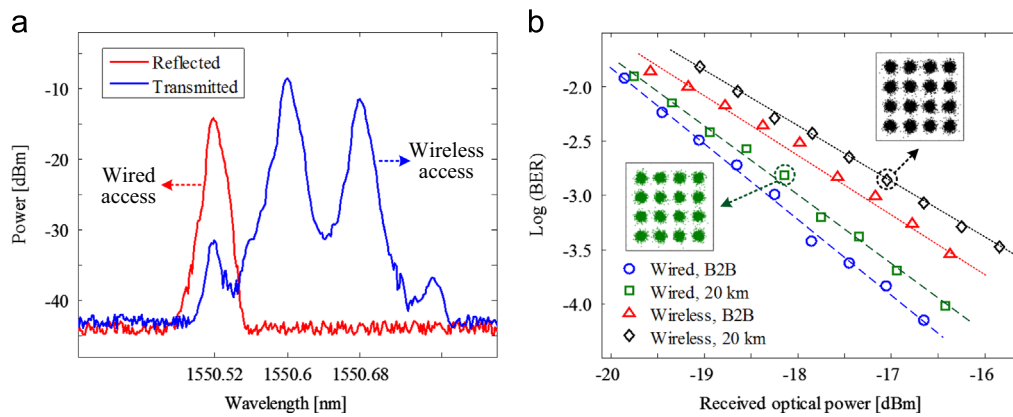


Fig. 10. Experimental results: (a) received optical spectra of wired and wireless access signals of CH₁; (b) measured BER performance of wired and wireless access for B2B and 25 km SSMF transmission and the corresponding constellations.

down-converted to baseband and then the obtained baseband OFDM signal is demodulated off-line by MATLAB. In the baseband OFDM demodulation, the serial data is converted to parallel and the CP is removed. After the fast Fourier transform (FFT), equalization and QAM demodulation, the final output data is generated for BER performance evaluation [19].

Fig. 10(a) shows the received optical spectra of wired and wireless access signals of CH₁. The reflected left first-order sideband of the OFDM-DSB signal is used for wired baseband OFDM access while the transmitted OFDM-SSB signal is used for wireless 10 GHz OFDM access. Measured BER performance for both wired and wireless access of the proposed hybrid WDM-OFDMA-PON is shown in Fig. 10(b). The received sensitivities at a BER of 3×10^{-3} for wired baseband OFDM access and wireless 10 GHz OFDM access after 20 km SSMF are -18 and -16.7 dBm, respectively. A power penalty of about 1.3 dB has been observed for the wired and the wireless access. The measured corresponding constellations for both wired and wireless 16-QAM OFDM signals are also inserted in Fig. 10(b).

5. Conclusions

We have theoretically analyzed and experimentally verified the scalable and reconfigurable generation of flat optical comb by using the proposed TCG. The experimental results agree well with the theoretical prediction about flatness and scalability of the obtained optical comb. Reconfigurability and stability of the obtained optical comb have also been discussed in the experimental verification. The feasibility of employing the obtained flat optical comb as the WDM optical source for a WDM-RoF system and a hybrid WDM-OFDMA-PON has been successfully proved by two corresponding experimental demonstrations. An average Rx sensitivity for all 17 WDM channels at the BER of 10^{-9} after 25 km SSMF is about -18.5 dBm in the WDM-RoF system, while a power penalty of about 1.3 dB has been observed for the wired and the wireless access in the hybrid WDM-OFDMA-PON.

Acknowledgments

This work is supported partly by National Natural Science Foundation of China Nos. 61171045, 61301156 and 61101095,

Program for New Century Excellent Talents in University (No. NCET-13-0099), Fundamental Research Funds for the Central Universities (No. ZYGX2013J005), Open Fund of State Key Laboratory on Local Fiber-Optical Communication Networks and Advanced Optical Communication Systems at Shanghai Jiao Tong University (No. 2013GZKF031301), and Open Fund of State Key Laboratory of Information Photonics and Optical Communications at Beijing University of Posts and Telecommunications.

References

- [1] M.C. Yuang, C. Lam, H. Kuwahara, A. Willner, *IEEE J. Sel. Areas Commun.* 28 (6) (2010) 769.
- [2] E. Wong, *J. Lightwave Technol.* 30 (4) (2012) 597.
- [3] D. Wake, A. Nkansah, N.J. Gomes, *J. Lightwave Technol.* 28 (16) (2010) 2456.
- [4] M. Fujiwara, J. Kani, H. Suzuki, K. Araya, M. Teshima, *Electron. Lett.* 37 (15) (2001) 967.
- [5] T. Ohara, H. Takara, T. Yamamoto, H. Masuda, T. Morioka, M. Abe, H. Takahashi, *J. Lightwave Technol.* 24 (6) (2006) 2311.
- [6] R. Maher, K. Shi, L.P. Barry, J. O'Carroll, B. Kelly, R. Phelan, J. O'Gorman, P.M. Anandarajah, *Opt. Express* 18 (15) (2010) 15672.
- [7] C.F.C. Silva, A.J. Seeds, P.J. Williams, *IEEE Photon. Technol. Lett.* 13 (4) (2001) 370.
- [8] V.R. Supradeepa, A.M. Weiner, A broadband, spectrally flat, high rep-rate frequency comb: bandwidth scaling and flatness enhancement of phase modulated CW through cascaded four-wave mixing, in: *Proceedings of the OFC/NFOEC 2011*, Paper OMQ3.
- [9] C.H. Chang, P.C. Peng, H.H. Lu, C.L. Shih, H.W. Chen, *Opt. Lett.* 35 (23) (2010) 4021.
- [10] S. Ozharar, F. Quinlan, I. Ozdur, S. Gee, P.J. Delfyett, *IEEE Photon. Technol. Lett.* 20 (1) (2008) 36.
- [11] J.W. Zhang, J.J. Yu, L. Tao, Y. Fang, Y.G. Wang, Y.F. Shao, N. Chi, *J. Lightwave Technol.* 30 (24) (2012) 3911.
- [12] T. Sakamoto, T. Kawanishi, M. Izutsu, *Opt. Lett.* 32 (11) (2007) 1515.
- [13] I.L. Gheorma, G.K. Gopalakrishnan, *IEEE Photon. Technol. Lett.* 19 (13) (2007) 1011.
- [14] T. Healy, F.C.G. Gunning, A.D. Ellis, J.D. Bull, *Opt. Express* 15 (6) (2007) 2981.
- [15] C. He, S.L. Pan, R.H. Guo, Y.J. Zhao, M.H. Pan, *Opt. Lett.* 37 (18) (2012) 3834.
- [16] R. Wu, V.R. Supradeepa, C.M. Long, D.E. Leaird, A.M. Weiner, *Opt. Lett.* 35 (19) (2010) 3234.
- [17] W.M. Mao, P.A. Andrekson, J. Toulouse, Investigation of a spectrally flat multi-wavelength DWDM source based on optical phase- and intensity-modulation, in: *Proceedings of the OFC/NFOEC 2004*, Paper MF78.
- [18] Y.J. Dou, H.M. Zhang, M.Y. Yao, *Opt. Lett.* 36 (14) (2011) 2749.
- [19] C. Chen, C.F. Zhang, D. Liu, K. Qiu, S. Liu, *Opt. Lett.* 37 (19) (2012) 3954.
- [20] F.Z. Zhang, J. Wu, Y. Li, J.T. Lin, *Opt. Commun.* 290 (2013) 37.
- [21] C. Chen, C.F. Zhang, W. Zhang, W. Jin, K. Qiu, *Electron. Lett.* 49 (4) (2013) 276.
- [22] Y.Y. Won, H.S. Kim, Y.H. Son, S.K. Han, *J. Lightwave Technol.* 28 (16) (2010) 2213.
- [23] J.L. Wei, E. Hugues-Salas, R.P. Giddings, X.Q. Jin, X. Zheng, S. Mansoor, J.M. Tang, *Opt. Express* 18 (10) (2010) 9791.