



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

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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.

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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

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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

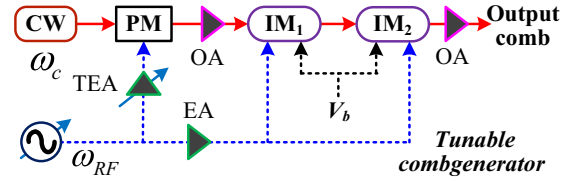


Fig. 1. Principle of the proposed TCG for scalable and reconfigurable generation of flat optical comb.

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

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

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

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