Tunable optical frequency comb enabled scalable and cost-effective multiuser orthogonal frequency-division multiple access passive optical network with source-free optical network units

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We propose and experimentally demonstrate a multiuser orthogonal frequency-division multiple access passive optical network (OFDMA-PON) with source-free optical network units (ONUs), enabled by tunable optical frequency comb generation technology. By cascading a phase modulator (PM) and an intensity modulator and dynamically controlling the peak-to-peak voltage of a PM driven signal, a tunable optical frequency comb source can be generated. It is utilized to assist the configuration of a multiple source-free ONUs enhanced OFDMA-PON where simultaneous and interference-free multiuser upstream transmission over a single wavelength can be efficiently supported. The proposed multiuser OFDMA-PON is scalable and cost effective, and its feasibility is successfully verified by experiment.

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Due to its high spectrum efficiency, strong robustness to chromatic dispersion, and great flexibility of dynamic bandwidth allocation, the orthogonal frequency-division multiple access (OFDMA) technology reveals significant potential for wide applications in the multiuser access passive optical networks (PONs) [1–3]. With the ever-increasing number of end-users, cost-effectiveness has become a key factor for the further development of PON systems, especially for the next-generation PON system requiring more than 64 optical network units (ONUs) [4]. Recently, investigations focused on the OFDMA-PON with colorless ONUs using lightwave centralization or signal remodulation approaches have been reported [5–7]. However, these techniques are aimed at making each ONU source-free from the upstream (US) laser. In [8], we have proposed a novel (to our knowledge) OFDMA-PON in which each ONU is source-free not only from the US laser but also from the radio-frequency (RF) source used for up and down conversions, by utilizing polarization multiplexing. Nevertheless, this scheme can only generate an RF source with a fixed frequency, and it is not applicable in multiuser access OFDMA-PON systems. In order to effectively support simultaneous multiuser US transmission over a single wavelength, RF sources with multiple frequencies are required to avoid signal overlapping on the US reused wavelength and thus eliminate the intersubcarrier interference within a single optical sideband as well as the interference between the subcarriers in the lower and upper optical sidebands [4]. An OFDMA-PON without high-speed ONU-side RF clock sources has been reported in [9], but coherent detection is required.

In this Letter, an advanced tunable optical frequency comb generator is introduced to efficiently provide multifrequency RF sources, in order to support simultaneous and interference-free multiuser US transmission over a single wavelength for the OFDMA-PON system.

Figure 1 shows the experimental configuration of the proposed tunable comb generator (TCG). It contains a continuous-wave (CW) laser, a sinusoidal RF source, a polarization controller (PC), a phase modulator (PM), an intensity modulator (IM), and a phase shifter (PS). In addition, two simplified control circuits are designed to control the peak-to-peak voltage (PPV) of PM driven signal and the output power of the generated comb, respectively. The PPV control circuit is comprised of an electric amplifier and a tunable electric attenuator, while the power control circuit is comprised of an optical amplifier and a tunable optical attenuator. Proposal of cascading a PM with an IM to get a multicarrier source has been reported in [10]. But this scheme lacks scalability, for it can only get a fixed number of carriers. A scalable scheme has been proposed in [11] also using the amplitude-phase hybrid modulation. But its scalability is achieved by adding costly WDM lasers to the input of the generator. Yet, in comparison, a cost-effective tunable comb source with scalability can be generated by dynamically controlling the PPV of a PM driven signal with only a single input laser. Therefore, this tunable comb source is of great significance in practical applications such as the next-generation multiuser

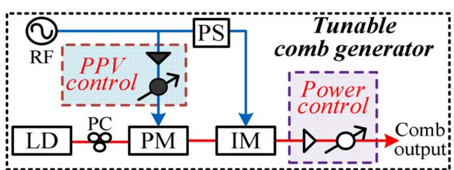

Fig. 1. (Color online) Configuration of the TCG. LD, laser diode; PPV, peak-to-peak voltage.

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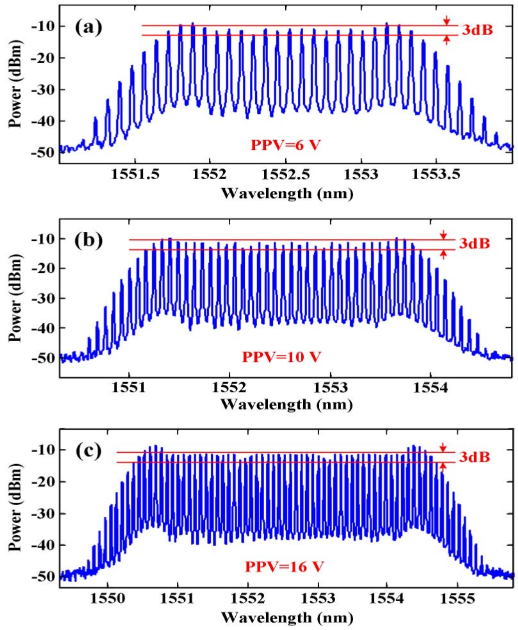

Fig. 2. (Color online) Optical spectra of optical frequency combs generated by the TCG. (a) PPV = 6 V, (b) PPV = 10 V, and (c) PPV = 16 V.

OFDMA-PON system where the end-users are continuously increasing.

Figure 2 gives three optical spectra of optical frequency combs generated by the TCG at three different PPVs of 6, 10, and 16 V with 0.01 nm resolution bandwidth. It is clear that the number of comb lines within the 3 dB fluctuation window is continuously increased with the enlarged PPVs of the PM driven signal. As the PPV is enlarged to 16 V, the number of comb lines within the 3 dB window reaches about 45. Furthermore, with the increasing number of comb lines, the comb performance such as the optical signal-to-noise ratio (OSNR) is relatively stable, which is measured by an optical spectrum analyzer (OSA) at 0.01 nm resolution. Therefore, this comb generation approach is scalable. The number of comb lines and the lowest OSNR within the 3 dB window are measured with the changes of PPVs, as illustrated in Fig. 3. The blue triangles show the relationship between the measured number of comb lines within the 3 dB window and the changes of the PPVs. As we can observe, the increase of the comb line number is nearly proportional to the increase of the PPVs. Meanwhile, for the measured

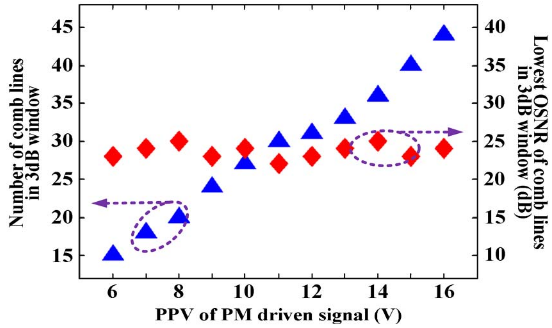

Fig. 3. (Color online) Measured number of comb lines and lowest OSNR within 3 dB window versus the PPV of a PM driven signal.

lowest OSNR within the 3 dB window, as shown in the red diamonds, there is no big fluctuation with the changes of the PPVs and it is relatively stable, near the 25 dB level. Hence, we can employ this TCG to generate RF sources with multiple frequencies for the use of multiuser access OFDMA-PON systems.

To verify the generation of multifrequency RF sources, a CW laser used as the optical source of the TCG can be given by

$$E_0(t) = E\cos(\omega_0 t + \varphi_0), \tag{1}$$

where E is the amplitude term and ω_0 and φ_0 are the angular frequency term and phase term, respectively. We assume that a flat comb with $2N + 1$ optical comb lines is generated, so the output of TCG can be expressed as

$$E(t) = E\sum_{n=-N}^{N}\cos[(\omega_0 + n\omega)t + \varphi_0], \tag{2}$$

where ω is the angular frequency term of the sinusoidal RF source. In order to generate the RF source, we assume that two comb lines i and j are selected to perform the optical heterodyning in a photodiode (PD) and the comb line N is used to carry the downstream (DS) OFDM signal, so we can define $-N \le i < j < N$. The current at the output of the PD within its limited bandwidth can be described as

$$I(t) = R|E_i(t) + E_j(t)|^2 = 2RE^2\cos[(j - i)\omega t], \tag{3}$$

where R is the responsivity of the PD. As can be seen from Eq. (3), an RF signal with a frequency equal to the frequency difference of two selected comb lines is obtained. From the definition of i and j, we can find out that the frequency range of the obtained RF signal is $\omega \sim 2N\omega$, with a frequency grid of ω. Thus, a flat comb with $2N + 1$ comb lines can be used to generate an RF signal with $2N$ different frequencies. In consequence, for an OFDMA-PON with multiple ONUs, such as 32 ONUs, we only need to control the PPV of the PM driven signal at about 13 V so as to generate 33 comb lines. Thus, 32 RF signals with different frequencies can be achieved to support the simultaneous and interference-free US transmission over a single wavelength for the OFDMA-PON system with 32 source-free ONUs.

The experimental setup of the proposed OFDMA-PON enabled by TCG is shown in Fig. 4. In order to better verify its feasibility as a bidirectional multiuser access system, a single-fiber topology is adopted. Meanwhile, a variable optical attenuator (VOA) with 12 dB attenuation is used following the 20 km standard single mode fiber (SSMF) to emulate a 1∶16 optical splitter. In the optical line terminal (OLT), a distributed-feedback (DFB) laser at 1552.52 nm is used as the optical source of the TCG and a 10 GHz sinusoidal RF source is employed to drive the cascaded PM and IM. In our proof-of-concept experiment, the PPV of the PM driven signal is controlled at 6 V by the PPV control circuit and the achieved optical comb source is shown in inset (i) in Fig. 4. There are 15 comb lines in the 3 dB window, and they are used to help configure the proposed OFDMA-PON system. As we can

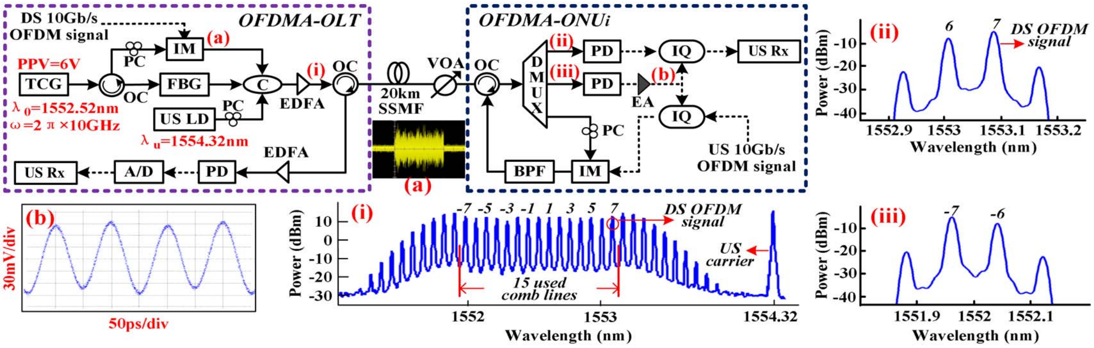

Fig. 4. (Color online) Experimental setup of the proposed OFDMA-PON and the obtained spectra. *C*, optical coupler; OC, optical circulator; IQ, inphase/quadrature mixer; A/D, analog-to-digital converter; Rx, receiver.

see from Fig. 4, comb line 7 is reflected back by a narrowband fiber Bragg grating (FBG) filter and directed into an IM by an optical circulator (OC) after passing a PC. Then it is modulated with the DS OFDM signal. As given in inset (a) in Fig. 4, the DS 10 Gb/s baseband 16 quadrature amplitude modulation (QAM)-OFDM signal with 3 GHz bandwidth is generated off-line with a fast Fourier transform (FFT) size of 128 and a cyclic prefix (CP) of 1/32 and uploaded into a Tektronix arbitrary waveform generator (AWG7102) at 10 Gsample/s with 8 bit resolution. Anther DFB laser at 1554.32 nm is combined together with modulated comb line 7 and other unmodulated comb lines. After a 20 dB erbium doped fiber amplifier (EDFA), the DS signal is generated with 24.7 dBm launch power, as shown in inset (i) of Fig. 4. After 20 km SSMF followed by a 12 dB VOA, the DS signal reaches the ith ONU with an input power of 8.8 dBm. In the ONU, a spectral demultiplexer (DMUX) with 20 GHz bandwidth and 5 dB loss in each output port is utilized to filter out the US optical source and two pairs of comb lines, respectively. The first pair is comb lines 6 and 7 with a frequency interval of 10 GHz, and comb line 7 carries the DS OFDM signal, as shown in inset (ii) in Fig. 4. A 10 GHz linear PD is used to perform the optical heterodyning of this pair of signals, and then the DS 10 GHz OFDM signal is generated. The second pair is comb lines −7 and −6, also with a frequency interval of 10 GHz, and both comb lines are unmodulated, as depicted in inset (iii) in Fig. 4. After beating in another 10 GHz PD, we can obtain a pure 10 GHz RF source, shown in inset (b) in Fig. 4. Then the obtained 10 GHz pure RF source is used to downconvert the DS 10 GHz OFDM signal and upconvert the US baseband 16QAM-OFDM signal, which is generated off-line with an FFT size of 128 and a CP of 1/32. The US 10 GHz OFDM signal is modulated onto the US laser via an IM and an optical bandpass filter (BPF) to generate the US single sideband OFDM signal. Then the US signal is transmitted back to the OLT for performance evaluation.

Figure 5 shows the measured bit-error-rate (BER) curves and the normalized constellations for the proposed OFDMA-PON system. The power penalty for DS and US transmissions is less than 0.4 dB at a BER of 10^{-3}. After 20 km SSMF, the received 16QAM constellations have been effectively recovered for both DS and US receptions.

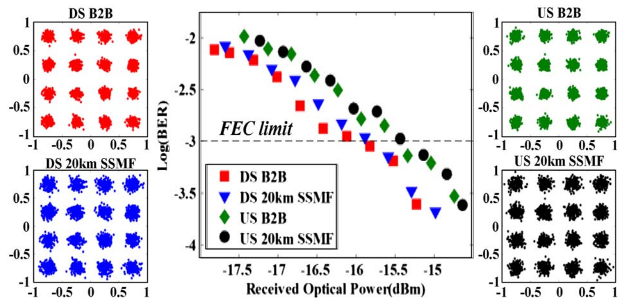

Fig. 5. (Color online) Measured BER curves and normalized constellations for both DS and US transmissions after back-to-back (B2B) and 20 km SSMF. FEC, forward error correction.

We have proposed and verified a multiuser OFDMA-PON in which all the ONUs are source-free from both the US laser and the RF source used for up/down conversions, enabled by tunable comb generation. A desired number of multifrequency RF sources can be achieved thanks to the scalability of the TCG. Consequently, the proposed multiuser OFDMA-PON is scalable and cost-effective, and it is promising for application in the next-generation broadband optical access networks.

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