Novel scheme enabling broadcast signal transmission in WDM passive optical network

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We present a novel method for providing broadcast signal transmission in a wavelength division multiplexing passive optical network (WDM-PON). An unmodulated optical carrier for downstream transmission and a pair of unmodulated single-side band subcarriers are utilized for broadcast delivery and upstream transmission, respectively. System performance at 2.5-Gb/s down/upstream and 2.5-Gb/s broadcast transmission is also investigated.

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Wavelength division multiplexing passive optical network (WDM-PON) has been regarded as the ultimate choice for network access. Since the fiber to the home concept was proposed, this network type has been paid increasingly more attention. To the best of our knowledge, WDM-PON is not suitable for the intrinsic delivery of broadcast service. In spite of this, some efforts have been made to overcome this problem. Previously, some approaches to offer broadcast service were proposed using a single wavelength overlay on a time division multiplexing PON (TDM-PON)[1] or a broadband light source[2]. However, the former lowers the utilization rate of wavelength and the latter limits the transmission rate. Hence, the aforementioned schemes are not suitable for full-scale deployment. Later, subcarrier modulation (SCM) techniques[3,4] were employed to transmit downstream data and broadcast data. At the same time, upstream transmission can be solved by carrier reusing or subcarrier reusing, which can make the optical network unit (ONU) colorless and reduce user cost. Recently, some novel WDM-PON architectures to superimpose broadcast service onto the conventional unicast service in all wavelength channels[5,6] were studied. A main feature of these architectures is the selective transmission of broadcast service to particular subscribers. The advanced modulation format is well known to be a cost-effective way to increase transmission rate and improve system performance. Thus, a novel scheme with broadcast overlay based on polarization shift keying (PolSK)[7] modulation is proposed.

In this letter, we propose a novel and simple approach enabling the delivering of broadcast service. Here, we initially take advantage of the characteristics of subcarrier modulation. Then, we make full use of the generated SCM signal. In other words, the optical carrier and two single-side band (SSB) carriers of the SCM signal will be used for downstream, broadcast, and upstream transmission, respectively. Several similar approaches have been proposed to perform the broadcast function. Compared with these approaches[4,8,9], the utilization of unmodulated SCM signal can provide better performance, because all sources are pure for different transmissions. Here, the optical carrier is truly pure continuous wave (CW). On the other hand, when either the optical carrier or the subcarrier is reused for upstream transmission in these schemes, the differential phase-shift keying (DPSK) format always adopted at the optical line terminal (OLT) to reduce crosstalk between downstream/broadcast signal and upstream signal makes the system costly.

The proposed WDM-PON diagram is shown in Fig. 1. At the OLT, a multi-wavelength laser source (MLS)[10,11] is applied to guarantee multiple-wavelength emission simultaneously. A sinusoidal clock together with the MLS is used to drive the Mach-Zehnder Modulator (MZM) to generate multiple SCM signals. Subsequently, N unmodulated SCM signals pass through an interleaver (IL)[12] to separate optical carriers from double-side band (DSB) subcarriers. The spacing between the optical carrier and DSB subcarriers on either side of the optical carrier is 10 GHz. All optical carriers are then demultiplexed with an arrayed waveguide grating (AWG) and used as optical sources for downstream transmission, while subcarriers are further separated by another optical IL[13]. Afterward, all the down-SSB subcarriers are modulated by an intensity modulator (IM) for broadcast service and finally combined with multiplexed downstream signals for downlink direction transmission over the same single mode fiber (SMF). However, up-SSB subcarriers still act as CW lights directly sent to a remote note (RN) over another SMF. There are two AWGs in the RN: one is used as demultiplexer for downlink direction channels and the other is operated as both multiplexer and demultiplexer for uplink transmission. Naturally, the separated channels are connected to each ONU via separate distribution fibers. Each ONU is composed of a three-port filter for separating downstream unicast service and broadcast service, two receivers for detecting signals, respectively; and a modulator for upstream transmission. We have many approaches to enable upstream transmission, such as utilizing an injection locked Fabry-Perot laser diode (FP-LD) method. However, in order to simplify the architecture, we adopt direct modulation by using a reflective semiconductor optical amplifier (RSOA) to implement upstream transmission. Moreover, to make ONU colorless, a periodic filter such as a wavelength-tunable fiber Bragg grating (FBG) could be employed in a practical ONU.

To validate feasibility and superiority of the presented

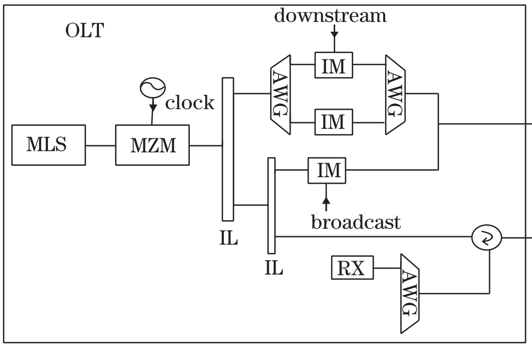

Fig. 1. Schematic configuration of the proposed WDM-PON.

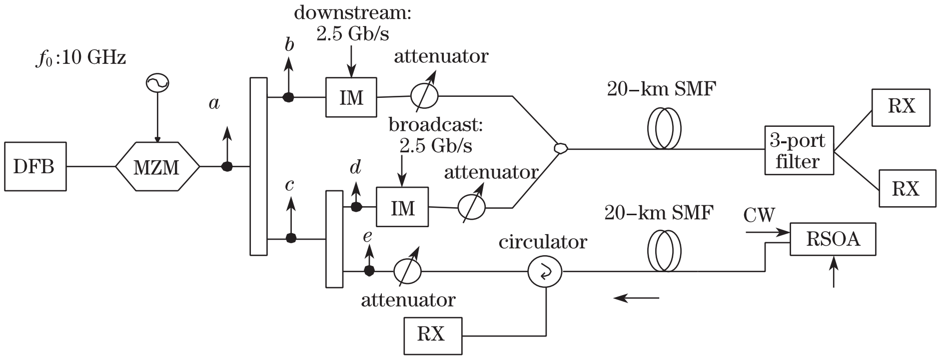

Fig. 2. Simulation setup of the proposed WDM-PON.

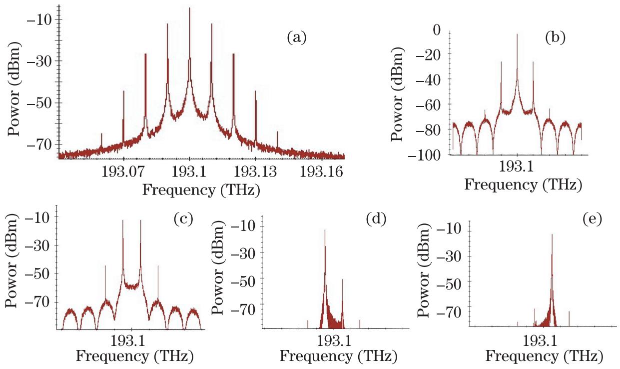

Fig. 3. Optical spectra with resolution of 0.001 nm. (a) SCM signal after MZM modulator; (b) separated optical carrier without modulation; (c) separated subcarriers without data; (d) down-SSB subcarrier; (e) up-SSB subcarrier.

method, the system is performed as illustrated in Fig. 2. At the OLT, a CW light from a distributed feedback (DFB) laser at 193.1 THz is fed into a MZM to generate an unmodulated SCM signal. The initial output power of the DFB laser is set at 3 dBm. Here, the MZM is driven by a 10-GHz sinusoidal clock without any data modulation. We measured the optical spectrum at five points (*a*, *b*, *c*, *d*, and *e*). Figure 3(a) shows the optical spectrum of this SCM signal at point *a*. Then, an IL with a free space range (FSR) of 20 GHz is employed to separate the optical carrier and the adjacent subcarriers (i.e., at 193.11 and 193.09 THz, respectively). The corresponding optical spectra at points *b* and *c* are shown in Figs. 3(b) and (c). Subsequently, the separated optical carrier is modulated via an IM driven at 2.5-Gb/s non-return to zero (NRZ) signal. The signal is generated from a pattern generator with a word length of 2^7–1 while the DSB subcarriers are further separated into two parts by another kind of IL. As shown in Figs. 3(d) and (e), at points *d* and *e*, the down-SSB subcarrier is performed as the optical source for 2.5-Gb/s broadcast signal transmission. In comparison, the up-SSB as a CW light source is directly injected into a RSOA over a 20-km SMF with a chromatic dispersion 16 ps/(nm·km). The modulated downstream signal and the broadcast signal are packed together over another SMF.

At the ONU, the combined downstream data and broadcast data need to be separated. Hence, a three-port filter with a bandwidth of 0.1 nm is selected with a central wavelength at the optical carrier wavelength. The downlink data and the broadcast data are then detected by the conventional baseband receivers, which simply consist of a photodetector (PD) and a low-pass filter. Here, the RSOA acts not only as a modulator but also as an amplifier. It just needs to work in the linear amplification region due to the CW injection. The output power of the seeded RSOA is 11 dBm. However, nonlinear effects such as stimulated Raman scattering (SRS) and self-phase modulation (SPM) could be ignored for such short-haul system. On one hand, due to the high threshold of SRS, it will not affect the system performance considerably. On the other hand, because of the accumulated dispersion, the SPM influence is also weakened. In addition, for the sake of symmetric transmission, the rate of upstream data is 2.5 Gb/s. The modulated upstream data are sent back to OLT over the 20-km fiber and at the OLT it is received by a 2.5-GHz PD after passing through a circulator.

System performance is evaluated by measuring the receiver sensitivities and eye diagrams of the downstream

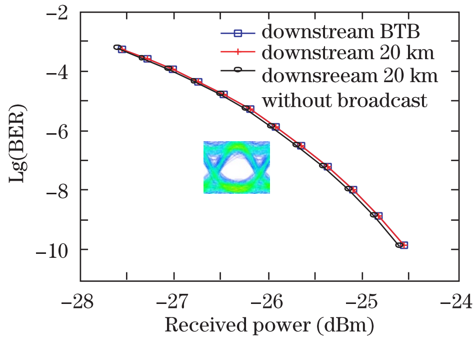

Fig. 4. BER curve and eye diagram of downstream transmission.

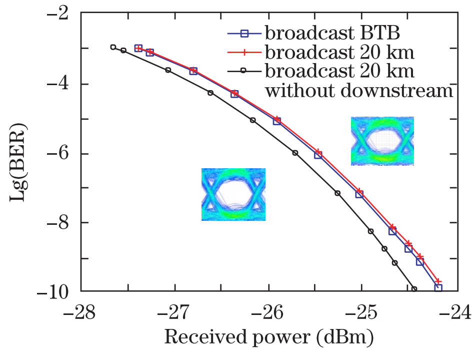

Fig. 5. BER curve and eye diagram of broadcast signal.

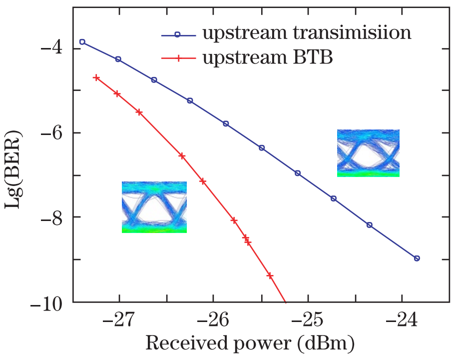

Fig. 6. BER curve and eye diagram of upstream transmission.

Table 1. Power Budget

	Downstream	Broadcast	Upstream
Power Fed into Each Transmission Link(dBm)	–4.37	–12.4	11 (after RSOA)
Coupler Loss(dB)	0.5	0.5	-
AWG Loss (RN) (dB)	4	4	4
20-km Fiber Loss(dB)	4	4	4
Filter Loss (ONU) (dB)	1	1	-
Circulator Loss(dB)	-	-	3
Total Loss(dB)	9.5	9.5	11
Receiver Sensitivity(dBm)	24.7	–24.2	–23.8
Power Margin(dB)	10.83	2.3	23.8

transmission, broadcast, and upstream transmission. Figure 4 shows the bit error rate (BER) of the downlink signal. After transmission over the 20-km SMF, the receiver sensitivity at the BER of 10^{-9} for 2.5-Gb/s downstream data is around –24.7 dBm. Moreover, there is almost no power penalty compared with the back to back (BTB) case. For the downlink transmission performance with and without broadcast exist, less than 0.1 dB-penalty is obtained. The eye diagram is also shown in the inset of Fig. 4.

Figure 5 shows the BER performance of the broadcast channel. The PIN receiver sensitivity at the BER of 10^{-9} after transmission is –24.2 dBm. Compared with the BTB case, the power penalty is negligible. We actually use optical carrier and SSB with carrier suppression for downstream and broadcast transmission, respectively. The fading effect induced by fiber dispersion can thus be ignored in the scenario. The power penalty to achieve the same BER of 10^{-9} in the case of with and without the downstream signal is about 0.3 dBm. Obviously, the power penalty of downstream transmission due to the existence of broadcast is slightly less than that of broadcast transmission due to the existence of downstream. As illustrated in Fig. 3(b), the optical carrier power to subcarrier power ratio (OCSR) is about 22 dB due to the suppression of the fundamental subcarrier. On the other hand, as illustrated in Fig. 3(d), the optical carrier is suppressed to 38.8 dB lower than the remaining sideband subcarrier. Thereby, crosstalk suffered by the downstream channel from subcarrier broadcast channel is much less than that suffered by the broadcast channel from downstream channel. In fact, both power penalties are low enough to be negligible.

The BER curve for the upstream data is shown in Fig. 6. After loop-back transmission, the receiver sensitivity at the BER of 10^{-9} is –23.8 dBm while the BTB errorfree ($\text{BER}<10^{-9}$) is achieved at –25.4 dBm. Performance over a 20-km fiber back and forth will degrade around 1.6 dB due to dispersion and backscattering noise. However, the eye diagram of received upstream signal is still clean after back and forth transmission.

The power budget is a key factor to evaluate the feasibility of the proposed architecture. Hence, we analyze the power budget for the broadcast signal, downstream signal, and upstream signal, respectively. Table 1 shows the details of the power budget. Clearly, the power budget is enough for the proposed architecture.

In conclusion, we have demonstrated a promising scheme that can deliver both point to point service and broadcast service. In this architecture, only one optical source can realize simultaneous transmission of point to point service and broadcast service via combining with SCM technology. By utilizing two kinds of ILs, the SCM signal can be separated into three parts, all of which are perfect CW lights for down/upstream transmission and broadcast transmission, respectively. Finally, we obtain good transmission performance of 2.5-Gb/s down/upstream transmission and 2.5-Gb/s broadcast transmission.

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