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Wavelength Conversion Based Colorless Optical Transmitter for Upstream DWDM PON

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***Abstract*-** In this paper, we proposed a novel colorless optical transmitter based on all-optical wavelength conversion using a reflective semiconductor optical amplifier (RSOA) for upstream transmission in dense wavelength-division-multiplexed passive optical networks. The proposed colorless optical transmitter for the optical network unit is composed of an electro-absorption modulated laser (EML), an optical coupler, and an RSOA. The proposed upstream optical transmitter is based on the fast gain recovery of the RSOA governed by carrier-carrier scattering and carrier-phonon interactions. Thus, it can potentially operate at >10 Gb/s. Two separate wavelength bands are allocated, one for the pump signals and the other for the probe signals. Therefore, the proposed transmitter operates in a colorless manner since the EML can have any arbitrary wavelength within the pump band. We demonstrate the transmission of a 10.7-Gb/s upstream signal generated by the proposed scheme in a single-fiber loop back-configured network.

***Keywords*-** *Passive optical network (PON), semiconductor optical Amplifier (SOA), Dense wavelength-division-multiplexing (DWDM).*

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I. INTRODUCTION

HIGH bandwidth applications such as storage networking, video streaming/sharing, and online gaming continue to drive greater bandwidth demands for next-generation broadband access networks. To address the growing capacity, security, and distance requirements while leveraging the benefits of a passive infrastructure, wavelength-division-multiplexed (WDM) passive optical networks (PONs) are considered to be the most scalable and future-proof solution. A key advantage of WDM PONs is the assignment of dedicated wavelength channels to each optical network unit (ONU) while having double-star architecture. This not only guarantees large capacity and high security for each ONU, but also facilitates graceful upgradability and network flexibility [1]–[3]. These merits not withstanding DWDM PONs are still considered prohibitively expensive due to the high installation, operation, and maintenance costs associated with the upstream wavelength-specific light sources required at the subscribers' premises. To lower the cost and make DWDM PONs a viable solution for broadband access networks, it is highly desirable to utilize colorless optical transmitters at the ONUs for upstream transmission. Identical optical transmitters which operate at any wavelength can be used for any ONUs to substantially lower the operation cost and consequently alleviate the inventory management issue. For this purpose, a couple of optical transmitters based on reflection-type opto-electronic devices, such as reflective semiconductor optical amplifier (RSOA) and incoherent light-injected Fabry-Perot laser diode, have been reported [4],[5]. In this approach, the reflection-type devices operate in a colorless manner by imposing upstream data on the incoming seed light from the central office (CO). Therefore, the wavelength- specific light sources can be all located at the CO, providing service providers with centralized management of the failure-prone light sources. However, the modulation bandwidth of the reflection-type opto-electronic devices is typically limited to less than 2 GHz by the carrier lifetime, which in turn, limits the upstream data rate in these schemes to Gb/s [6]. Thus, it is very challenging to operate these low-bandwidth devices at 10 Gb/s and beyond without the assistance of advanced modulation formats [7], post-detection electrical signal processing [8]. In this paper, we propose and demonstrate a novel approach to a colorless optical transmitter based on wavelength conversion. A high-speed optical signal generated from an electro-absorption modulated laser (EML) at the ONU is first wavelength-converted to the wavelength of the seed light by cross-gain modulation (XGM) in a gain-saturated RSOA. We experimentally demonstrate the transmission of 10-Gb/s upstream data over 20-km standard-single mode fiber (SSMF), investigate the dispersion-induced penalty, and study the conditions for colorless operation in the proposed scheme. The remaining parts of this paper are organized as follows. In Section II, we describe the architecture and the principle of operation of the proposed upstream transmitter. The experimental demonstration and the discussion of the experimental results are presented in Section III. Finally, this paper is summarized in Section IV.

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II. Architecture and Principle of Operation

The schematic diagram of an upstream WDM-PON system utilizing the proposed transmitter is illustrated in Fig. 1. A comb generator, which is, for example, composed of wavelength-division-multiplexed wavelength-specific laser diodes as shown in the figure, provides continuous wave (CW) light from $\lambda_1$to λ_N to *N* ONUs, where *N* is the number of channels, through the feeder fiber. This CW light serves to be injected into the RSOAs at the ONUs as seed light and is also referred to as a probe signal in this paper. At the ONU, an EML first generates a non-return-to-zero (NRZ) upstream optical signal at wavelength λ_{pumb}. The EML output (also referred to as a pump signal) is coupled to the CW seed light supplied from the CO and then sent to the RSOA where the wavelength conversion is performed. The upstream data of the pump light are imprinted onto the CW seed light through the XGM where the gain variation of the pump signal modulates the co-propagating CW light. Since the presence of the pump signal compresses the gain of the RSOA. The modulated probe signals ranging from λ_1 to λ_N are then multiplexed at the remote node and sent back to the CO for detection. At the CO, the upstream signals are first sent to a DI before being demultiplexed by an arrayed waveguide grating (AWG). It should be noted that in the proposed scheme both the probe and pump signals propagate back to the CO and thus it is necessary to filter out the pump signal using optical filters. To avoid using additional optical filters on the link, we can utilize non cyclic AWGs at the remote node and at the CO. In this case, λ_{pumb}, the wavelength of the pump signal, should be assigned outside the AWG pass band. As shown in Fig. 1(a) and (b), we have two wavelength bands within the RSOA gain spectrum, one for the probe channels and the other for the pump signals.The probe band falls exactly on the AWG passband so that the wavelength-converted probe signal can reach the CO for detection. However, the pump signal, the wavelength of which can be any wavelength outside the AWG passband, is filtered out by two AWGs, one at the remote node and the other at the CO. Note that the proposed wavelength-conversion-based transmitter operates in a colorless manner as long as the EML has any arbitrary wavelength within the pump band region. Thus, identical optical transmitters which satisfy the above band allocation requirements can be used for any ONUs in the proposed scheme. Our allocation scheme can suppress the pump signal by > 50dB since typical commercial non-cyclic AWGs have non-adjacent channel crosstalk better than 25 dB. Fig. 1 illustrates the upstream transmission only. In the proposed network, the downstream data could be accommodated by allocating additional waveband for downstream transmission.

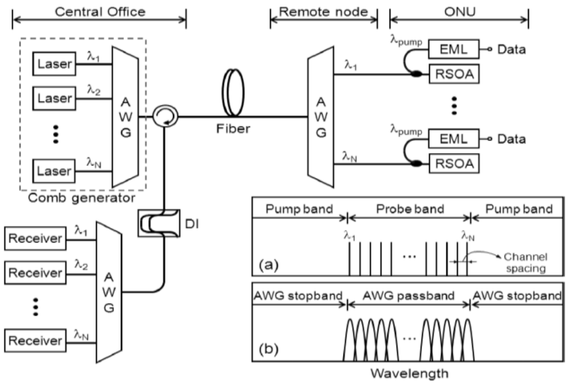

Fig. 1. The schematic diagram of an upstream WDM-PON system utilizing the proposed transmitter based on wavelength conversion. The insets show (a) an example of the wavelength band allocation for the pump and probe signals and (b) AWG spectrum of passband and stopband. AWG: arrayed waveguide grating, DI: delay interferometer, EML: electro-absorption modulated laser, ONU: optical network unit, and RSOA: reflective semiconductor optical amplifier.

III. Experimental Setup and Discussion

We demonstrate the proposed colorless optical transmitter for WDM PON upstream transmission using the experimental setup depicted in Fig. 2. A tunable laser source provides a CW probe signal at λ =1560 nm. We use a variable optical attenuator (VOA), VOA1, to adjust the power level of the probe signal. The CW probe signal is fed to an optical bandpass filter (OBPF), OBPF1, and then launched into SSMF before being sent to OBPF2. OBPF1 and OBPF2, which emulate the AWGs at the CO and the remote node, respectively, have a 3-dB bandwidth of 0.6 nm. At the ONU side, we have a tunable laser followed by an EAM to simulate an EML. This is to allow tuning the wavelength of the pump signal and thus to study the conditions for colorless operation in the proposed scheme. Upstream NRZ data running at 0.7 Gb/s with a pseudo-random binary sequence (PRBS) length of 2^{31}-1 are fed to the EAM for intensity modulation. Here, we assume Reed-Solomon (255, 239) forward- error correction (FEC)-coded data with a 7% over head. The extinction ratio (ER) of the pump signal is ~10 dB. The power level of the pump signal is adjusted at the EAM output using VOA2. The pump and probe signals are then combined by a 50:50 optical coupler and launched into an RSOA for wavelength conversion. The RSOA used in the experiment is an uncooled device housed in a transistor outline package. It is DC-biased at 50 mA and no high-speed signal is applied. Under this bias condition, the 3-dB spectral width of the RSOA output is measured to be 33 nm, ranging from 1529 to 1562 nm. Unless stated otherwise, the optical powers of the pump and probe signals injected into the RSOA are set to be -10 and -16 dBm, respectively. The input saturation power of the RSOA, defined as the input optical power at which the

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signal gain is compressed by 3 dB from its small signal gain, is measured to be -22 dBm. Thus, the RSOA operates in the saturation region. Polarization controllers (PCs) are inserted at the inputs of VOA1 and the polarization-sensitive RSOA to maximize the seeding and conversion efficiencies. The RSOA used in the demonstration has a polarization-dependent gain of -20 dB. Although the pump signal can give rise to a nonlinear polarization rotation, a change in the polarization state of the probe signal in the presence of the pump signal polarization-insensitive RSOAs can be used for real systems to eliminate the need for PCs. The output power of the wavelength-converted signal at 1560 nm is 2.5 dBm when the optical power of the injected pump signal at 1550 nm is -10 dBm. The converted upstream signal at λ_{probe} is sent back to the CO over the same feeder fiber. The signal is then fed to a DI with an FSR of 16.1 GHz. We use an optically pre-amplified receiver comprising an Erbium-doped fiber amplifier (EDFA), OBPF3 (bandwidth = 0.6nm), and a PIN detector. The two optical filters on the upstream link, OBPF2 and OBPF3, suppress the pump signal by >50dB when $|\lambda_{pumb} - \lambda_{probe}| > 2$ nm.

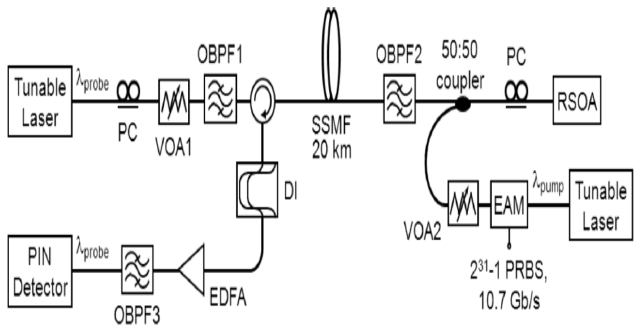

Fig.2 Experimental setup DI: delay interferometer, EAM: electroabsorption modulator, EDFA: Erbium-doped fiber amplifier, OBPF: optical band-pass filter, PC: polarization controller, PRBS: pseudo-random binary sequence, RSOA: reflective semiconductor optical amplifier, SSMF: standard single-mode fiber, and VOA: variable optical attenuator.

IV. Experimental Results

We first measure the optical spectra of the upstream signal before and after the DI, as shown in Fig. 3.Also shown in the figure is the transmittance curve of the DI. The peak wavelength of the DI transmittance is located 0.036 nm shorter than the upstream signal, which is fixed throughout the experiment. Thus, the DI serves to filter out the red-shifted chirp, which is induced by the refractive index modulation of the RSOA during the wavelength conversion.

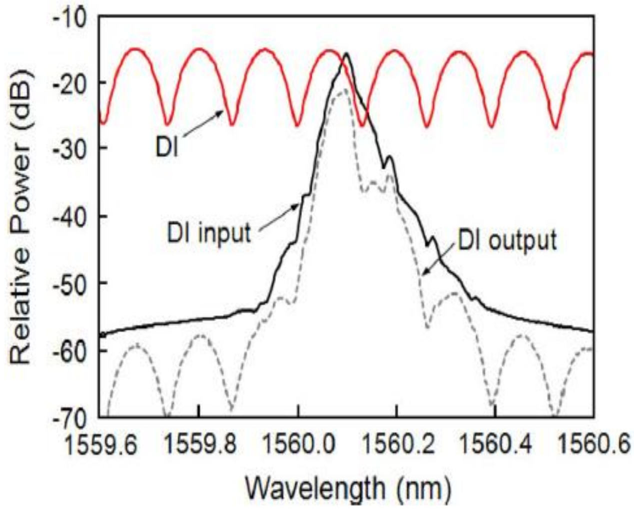

Fig.3. Measured optical spectra at the DI input (solid black) and at the DI output (dashed grey). The transmittance curve of the DI is plotted in red.

This chirp tailoring created by the off-center filtering greatly improves the receiver sensitivity as well as the dispersion tolerance of the upstream signal, which will be shown later in this section.

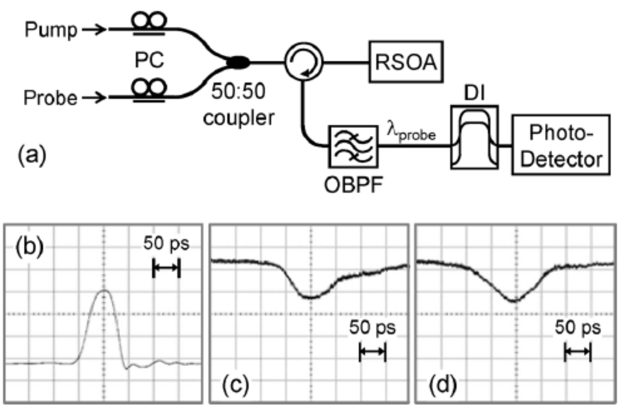

Fig. 4. (a) Experimental setup to measure the gain recovery time of the RSOA. (b)Waveformof the 60-ps pump signal. (c)Waveformof the probe signal before the DI. (d) Waveform of the probe signal after the DI.

To measure the gain recovery time of the RSOA, we setup an apparatus as shown in Fig. 4(a) . A 60-ps pulsed pump signal at 1550 nm, as shown in Fig. 4(b), is first combined with a CW probe signal at 1560 nm and then launched into the RSOA through an optical circulator. After the wavelength conversion, we filter out the pump signal using an OBPF having a 3-dB bandwidth of 0.6 nm. The DI is used at the output of the OBPF. The signal is detected with a high-speed detector. Fig. 4(c) shows the gain recovery of the RSOA in the absence of the DI.

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It shows the typical SOA gain recovery. The leading edge (i.e., falling edge) is determined by the pump pulse duration. The trailing edge (i.e., rising edge) is known to be governed by three different timescales. Fast gain recovery on sub picosecond and a few picoseconds timescales driven by carrier-carrier scattering and carrier-phonon interactions, respectively and slow gain recovery driven by electron-hole interactions on a nanosecond timescale. Fig. 4(d) shows the waveform of the probe signal in the presence of the DI. The improved bandwidth performance by use of the DI is also manifested through a modulated data pattern. To guarantee the colorless operation of the proposed scheme, the pump wavelength should be any arbitrary wavelength within the pump band. Thus, we measure the receiver sensitivity of the upstream signal while tuning the wavelength of the pump wavelength. The 20-km SSMF is placed back in the loop-back configuration as shown in Fig. 2. Depending upon whether the pump wavelength is shorter or longer than the probe wavelength, we have wavelength up- or down-conversion. The transmission distance is 20 km. Fig. 5(a) shows the receiver sensitivity versus the injected pump power into the RSOA when the probe power is -16 dBm. When the pump power is lower than -11 dBm, the pump power is not sufficient enough to operate the RSOA in a deep saturation region, inducing some sensitivity penalties. On the other hand,

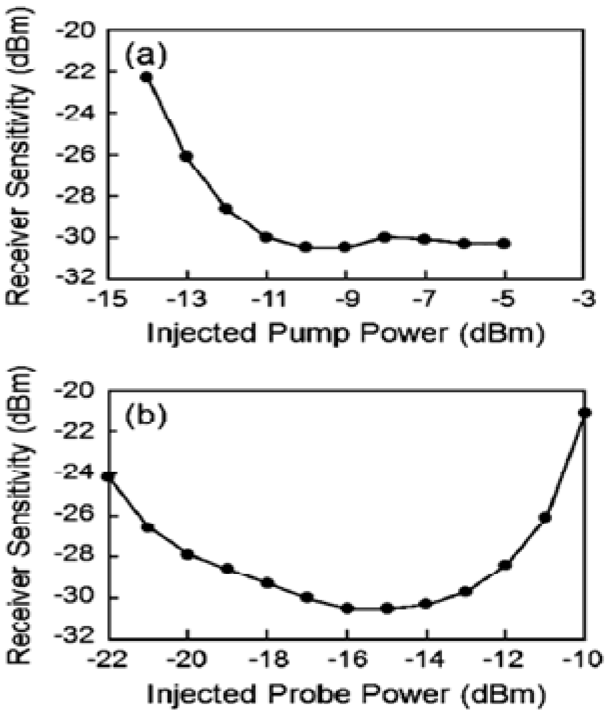

Fig.5. (a) Measured receiver sensitivity as a function of the injected pump power into the RSOA when the probe power is dBm. (b) Measured receiver sensitivity as a function of the injected probe power into the RSOA when the pump power is dBm. The transmission distance is 20 km. and are 1550 and 1560 nm, respectively.

strong pump power improves the receiver sensitivity, leveling it off at around -30 dBm. The effect of the probe power on the system performance is plotted in Fig. 5(b). The pump power is fixed to -10 dBm in this figure. The result shows that we have an optimum range of injected probe power, which ranges from -19 to -12 dBm for 2-dB penalty window. In a WDM-PON system using the proposed scheme, the injected pump power can be readily adjusted since both the EML and RSOA are located at the same place. Besides, as shown in Fig. 5(a), the required pump power for injection is > -11dBm, which is translated into > -8 dBm at the output of the EML. This can be easily satisfied by using commercially available EMLs. The power budget of a loop-back configured network can be limited either by the injection power requirements or the power difference between the available transmitter power and the receiver sensitivity. In our demonstration, we have a power difference of 33 dB [= 2.5 dBm (RSOA output power) +30.5 dBm (receiver sensitivity)]. On the other hand, the required optical power of the CW probe signal is -19 dBm. Therefore, the power budget of the WDM-PON system utilizing the proposed transmitter would be limited by the injection power requirement of the CW probe signal. With the fiber launch power of 6 dBm, the system can accommodate a total link loss of 25 dB(= 6 +19). Taking into account the loss of 20-km fiber (6 dB), an AWG (5 dB) at the remote node, and a 50:50 coupler (3 dB) at the ONU, we have a power margin of 11 dB.

V. Conclusion

We have proposed and demonstrated a novel colorless optical transmitter based on all-optical wavelength conversion for upstream DWDM- PON systems. The proposed optical transmitter at the ONU side is composed of an electro-absorption modulated laser, an optical coupler, and a reflective semiconductor optical amplifier. Thus, it could be implemented potentially in a cost-effective manner through monolithic integration. Our experimental demonstration performed at 10.7 Gb/s shows that the proposed scheme works over 30 nm of either the pump (i.e., EML output) or probe (i.e., seed light) wavelength. Therefore, the proposed optical transmitter operates in a colorless manner since the EML wavelength can be chosen arbitrarily within this wavelength range. Unlike other colorless optical transmitters based on directly modulated semiconductor opto-electronic devices, the modulation bandwidth of which is limited by the carrier life time in the active layer, the performance of the proposed transmitter is limited by fast carrier dynamics of the RSOA. Thus, we expect the proposed scheme could be used as an alternative solution to reflective electroabsorption modulator-SOA-based transmitter to implement high-capacity DWDM PONs operating at 10 Gb/s/channel and beyond.

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