Demonstration of Low-Cost Uplink Transmission in a Coherent OCDMA PON Using Gain-Switched Fabry–Pérot Lasers With External Injection

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***Abstract*—We propose and demonstrate a simple and low-cost uplink transmission scheme for coherent optical code-division multiple access (OCDMA) passive optical networks (PONs), using gain-switched Fabry–Pérot (GS-FP) lasers with external injection as local light sources at optical network units. Experimental results based on the two-user 1.25-Gb/s OCDMA system confirm the feasibility of this scheme. The system performance is compared with that of the OCDMA system using a conventional mode-locked laser (MLL). The auto-correlation peak to the maximum wing level (P/W) ratio is also given as the central wavelength of the GS-FP laser varies. The present low-cost scheme is highly preferable for OCDMA PON applications.**

***Index Terms*—Fabry–Pérot (FP) laser, gain-switching, optical code-division multiple access (OCDMA), passive optical network (PON).**

I. INTRODUCTION

PASSIVE optical networks (PONs) have been attracting enormous research interest due to their low operational costs and huge bandwidth. Optical code-division multiple access (OCDMA) [1] is a promising multiple-access method for PONs, since it can offer various system benefits including asynchronous operation, protocol transparency, simplified network control, and enhanced security [2]. One of the important topics for OCDMA PONs is to reduce the hardware cost, especially on the user side or the optical network units (ONUs). In many of the recently demonstrated OCDMA systems, short-pulse laser sources, such as mode-locked lasers (MLLs), have been adopted [3]–[5]. However, they are not suitable for the applications at ONUs of OCDMA PONs due to their high cost. An optical pulse distribution approach has been proposed in [6], in which there is no need for short-pulse sources on the ONU side due to the broadcast of unmodulated pulses from the optical line terminal (OLT) to all ONUs. However, ONUs at various distances from the OLT will receive optical pulses with quite different qualities because of the fiber dispersion. Therefore, a low-cost local optical pulse source is preferred for ONUs in the practical implementation of OCDMA PONs. Several pulse sources, including pulse carving distributed-feedback (DFB) lasers [7], [8] and multiwavelength injection locking Fabry–Pérot (FP) lasers [9]–[11], have been introduced to the OCDMA systems. Compared with the former, the FP lasers are of much lower cost. However, the existing OCDMA light sources based on FP lasers often have broad pulsewidths and the feasibility has not yet been confirmed in a high speed and multiuser OCDMA system.

In this letter, we propose an uplink transmission scheme for coherent OCDMA PONs. For the local optical pulse source at each ONU, we employ a gain-switched FP (GS-FP) laser with external injection, which is considered as a simple, low-cost but high-quality short-pulse source [12]. A two-user 1.25-Gb/s OCDMA system based on the GS-FP laser with a pulsewidth of around 19 ps is experimentally demonstrated and the system performance is compared with the OCDMA system using a conventional MLL. Furthermore, we also investigate how the auto-correlation peak to the maximum wing level (P/W) ratio changes with the central wavelength shift of the GS-FP laser.

II. PROPOSED UPLINK TRANSMISSION SCHEME

Fig. 1 shows the architecture of an OCDMA PON with our proposed scheme, which employs GS-FP lasers with external injection at the ONUs. A continuous-wave (CW) laser used to injection lock the FP lasers is located at the OLT to reduce the cost and relax the management on the user side. The injecting CW light is first combined with the encoded downlink signals by a coarse wavelength-division multiplexer (CWDM) and then transmitted to the ONUs through a $1:N$ power splitter at the remote node (RN). At each ONU, another CWDM is used to separate the injecting light from the encoded downlink signals. Then the separated CW light is injected into the FP laser, while the received encoded signals are decoded by a matched decoder to obtain the desired channel. Short pulses produced from the GS-FP laser are modulated by uplink data, then encoded and transmitted back to the OLT.

III. EXPERIMENT AND COMPARISON

The experimental setup of a two-user 1.25-Gb/s coherent OCDMA system employing the GS-FP laser with external

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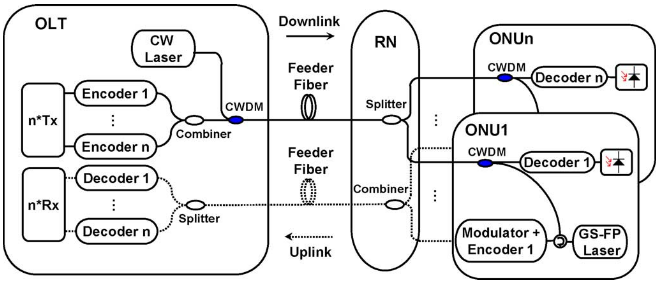


Fig. 1. Architecture of an OCDMA PON with GS-FP lasers at the ONUs. GS-FP laser: gain-switched FP laser.

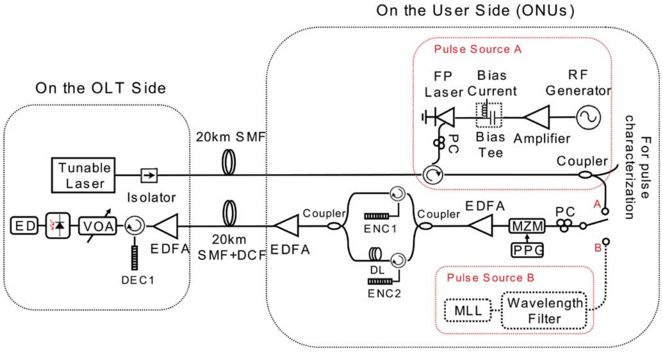


Fig. 2. Experimental setup. Case A: GS-FP laser; Case B: MLL followed by optical filter. PPG: programmable pattern generator; ENC: encoder; DEC: decoder; EDFA: erbium-doped fiber amplifier; ED: error detector; VOA: variable optical attenuator.

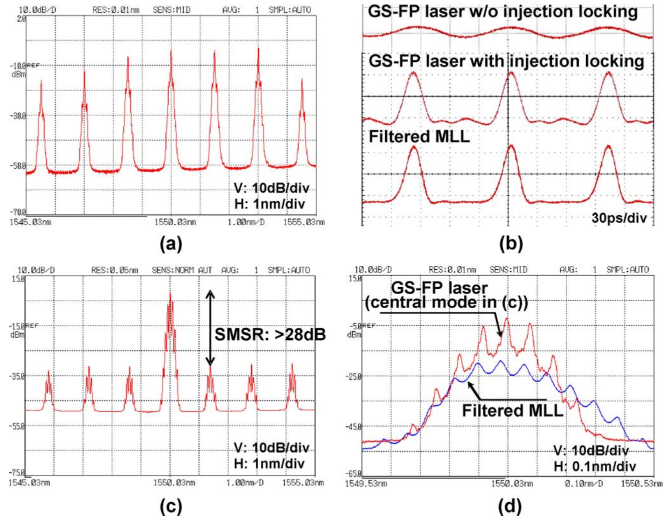


Fig. 3. Output of the GS-FP laser. (a) spectrum for the GS-FP laser (without injection locking); (b) patterns of the 10-GHz optical pulse trains; (c) spectrum for the GS-FP laser (with injection locking); (b) spectra for the filtered MLL (blue) and GS-FP laser (red). V: vertical; H: Horizontal.

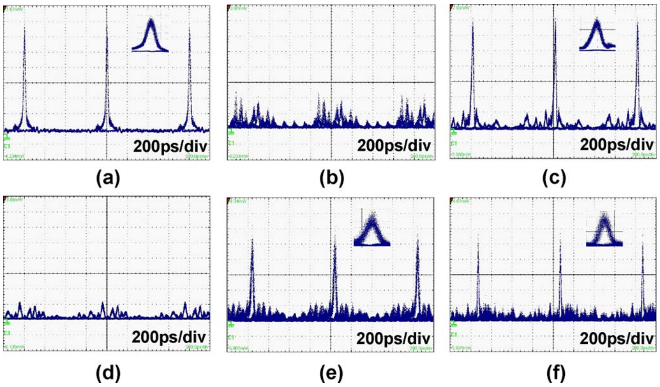
injection is illustrated in case A of Fig. 2. Previously we have demonstrated the downlink transmission using the MLL [13]. Here we only show the uplink channels utilizing the low-cost GS-FP laser. The FP laser used is a commercial 1.55-μm multiple quantum-well (MQW) laser module with cooled package, and has a threshold current of 13 mA and a longitudinal mode spacing of 1.5 nm at 25°C. To realize the gain-switching operation, a dc bias current in conjunction with an amplified sinusoidal signal is applied to the laser. In our experiment, the external injection seed is provided by a tunable CW laser in order to tune the central wavelength of the GS-FP laser. In practical implementations, a DFB laser with central wavelength at one of the FP laser's modes can be used instead [11]. A 20-km single-mode fiber (SMF) is placed between the isolator and the circulator to represent the downlink feeder fiber. Two polarization controllers (PCs) are employed on the ONU side: one is located before the GS-FP laser for controlling the polarization state of the injection light from OLT, and the other is used before the Mach–Zehnder modulator (MZM). The matched polarization state can be obtained after carefully adjusting the PCs and the polarization stability is good enough for our measurements. However, in a practical application, a depolarizer at OLT can be used to eliminate the polarization dependence of injection locking, as proposed in [14], and the PC before the modulator can be replaced by using a polarization-maintaining fiber pigtailed MZM.

The output pulse train from the circulator is split into two parts. One part is characterized by using an optical spectrum analyzer with a resolution of 0.01 nm and a Tektronix (DSA8200-80C10B) sampling oscilloscope with 80-GHz bandwidth and 6-ps time resolution for the optical channel. The other part is modulated by an MZM with $2^7 - 1$ pseudorandom bit sequence (PRBS) at 1.25 Gb/s. The amplified optical signal is equally split into two paths and encoded by two 127-chip, 320-Gchip/s superstructured fiber Bragg gratings (SSFBGs). An optical delay line (DL) is used to decorrelate the two encoded signals. After that, the encoded signals are recombined, amplified, and launched into another 20-km SMF followed by a dispersion-compensation fiber (DCF). On the OLT side, one of the uplink channels are decoded by the matched SSFBG and direct detection is used for signals reception. For comparison, we also test a two-user 1.25-Gb/s OCDMA system with an MLL as pulse source, which is shown in case B of Fig. 2. An optical bandpass filter is applied after the MLL to generate a pulse train with similar pulsewidth and bandwidth as those of the GS-FP laser output.

IV. RESULTS AND DISCUSSION

The commercial FP laser used in our experiments has a bandwidth of about 6 GHz in free running. Without external light injection, there is nearly no pulse output at 10 GHz from the GS-FP laser, as shown in Fig. 3(b). With −4.3-dBm external CW light injection, the sidemode suppression ratio (SMSR) of the FP laser exceeds 28 dB [comparing Fig. 3(a) and (c)] and 10-GHz optical pulses with a pulsewidth of around 19 ps can be generated from the GS-FP laser [see Fig. 3(b)]. The bandwidth of a GS-FP laser can be dramatically increased through proper external light injection [12]. Here we note that in a practical OCDMA PON, the large splitting loss of the $1:N$ splitter may limit the maximal power of the external injection light reaching ONUs. However, this power loss can be compensated by a preamplifier in each ONU. We also show in Fig. 3(b) the pulse train from the wavelength-filtered MLL, whose pulsewidth is about 17 ps. The spectrum of the filtered MLL is shown in Fig. 3(d), compared with the central longitudinal mode of GS-FP laser in Fig. 3(c).

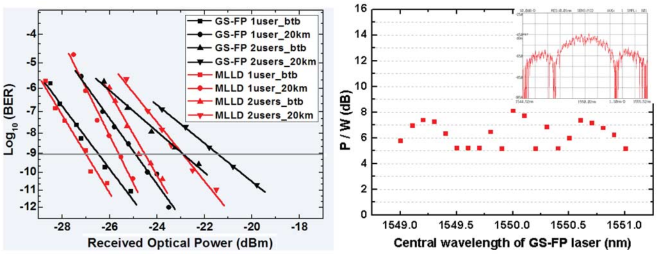
The measured eye diagrams are illustrated in Fig. 4. From the eye diagrams in Fig. 4(e) and (f), one sees that the case of GS-FP



(a) (b) (c)

(d) (e) (f)

Fig. 4. Eye diagrams. The case of GS-FP laser: (a) modulated signal before the encoders; (b) encoded signals for the case of two users; (c) signal after matched decoding; (d) signal after mismatched decoding; (e) decoded signal after 20-km transmission, two users. For comparison, the case of MLL (f) decoded signal after 20-km transmission, two users.



(a) (b)

Fig. 5. (a) BER curves; (b) P/W ratio as the central wavelength of GS-FP laser varies within the 3-dB reflecting spectrum of SSFBG (shown in the inset).

laser gives similar performance as the case of the wavelength-filtered MLL in terms of multiple access interference (MAI). The BER curves in Fig. 5(a) show that for two users after 20-km transmission the proposed scheme with the GS-FP laser has a power penalty of around 1.5 dB (at BER $= 10^{-9}$), as compared with the scheme with the wavelength-filtered MLL. This, we believe, should be acceptable. Together with their high cost-effectiveness, GS-FP lasers are thus very competitive candidates for OCDMA PON applications.

We further investigate the P/W performance of the decoded signal when the central wavelength of the FP laser changes within the 3-dB bandwidth ($\sim$2 nm) of the "reflecting band" of SSFBG, and the results are shown in Fig. 5(b). As one can see, although the highest P/W is found when the center wavelength is tuned to match that of the encoder/decoder, the P/W ratio fluctuates in a region between 5 and 8.2 dB as the central wavelength varies. The limited P/W ratio is caused by the relatively broad pulsewidth of the generated pulses from GS-FP laser, which is larger than the chip duration ($\sim$3 ps) of the present SSFBG en/decoder with 127 chips. The SSFBGs used in [7] and [8] with chip duration of more than 20 ps may be choices to compensate this degradation. However, bit rate or security of the OCDMA system will be decreased in this case.

V. CONCLUSION

We propose and first demonstrate a low-cost uplink transmission scheme for a coherent OCDMA PON, which employs GS-FP lasers with external injection as the light source at ONUs. Compared with the OCDMA system using light source of the conventional MLL, our two-user 1.25-Gb/s OCDMA system based on the GS-FP laser gives reasonable experimental performance with much lower cost. The P/W performance with central wavelength shift of the GS-FP laser is also analyzed and discussed.

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