A UWB Over Fiber System Compatible With WDM-PON Architecture

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***Abstract*—We present a novel ultra-wideband (UWB) over fiber system that is compatible with wavelength-division-multiplexing passive optical network architecture based on a Fabry–Pérot laser diode (FP-LD). Through external injection, the FP-LD operates as an active optical filter. By locating the optical carrier of a phase-modulated injection optical signal at one slope of the filter response, phase-modulation to intensity-modulation conversion is achieved, leading to the generation of a UWB signal having a power spectrum meeting the FCC-specified spectral mask. The proposed system is experimentally evaluated, with eye diagrams and bit-error rates measured. An error-free operation is achieved after 20-km single-mode fiber transmission for both cases where the FP-LD is placed in the center office and the remote site. The power penalty for the transmission is less than 3.2 dB.**

***Index Terms*—Fabry–Pérot laser diode (FP-LD), passive optical network (PON), ultra-wideband (UWB), wavelength-division multiplexing (WDM).**

I. Introduction

Ultra-wideband (UWB) is considered a promising approach to providing a low complexity, low cost, low power consumption, and high data-rate wireless connectivity in the future wireless local area networks (WLANs) and wireless personal-area networks (WPANs) [1]. Due to the low power spectrum density (PSD) regulated by the U.S. Federal Communications Commission (FCC), the typical communication distance of a UWB system is limited to only a few meters to tens of meters. To increase the area of coverage and to offer the availability of undisrupted service across different networks, a solution called UWB over fiber is proposed [2]. Different UWB over fiber systems have been reported recently [3]–[7]. To practically deploy these systems at a low cost, a solution is to integrate the UWB over fiber systems into the current or future wired optical access networks [8], [9]. Concerning the wired optical access networks, Gigabit passive optical network (GPON) according to ITU-T G.984 has been widely deployed in the U.S. and Europe. Meanwhile, Ethernet PON (EPON) according to the Ethernet-First-Mile standard or IEEE 802.3ah is broadly deployed in Japan and Korea. However, both GPON and EPON are based on time-division multiple access (TDMA) technology, providing services to N users by use of passive $1:N$ power splitters with an aggregate bit rate, so they cannot keep up with the requirements of future access network evolution regarding aggregated bandwidth, attainable reach, and allowable power budget. As a result, there is a worldwide consensus that the current TDMA PON (i.e., EPON and GPON) would evolve toward wavelength-division-multiplexing PON (WDM-PON) [10]. Previously, Prince *et al.* demonstrated that a UWB service can be provided in a WDM-PON network by adding a UWB signal generator in the center office and a UWB receiver in the remote site [8].

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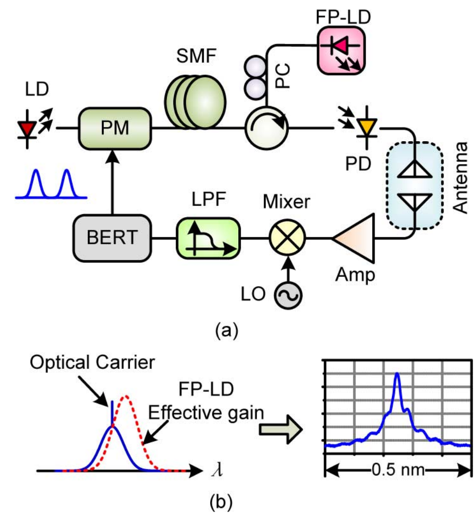

Fig. 1. (a) Experimental setup of the UWB over fiber system compatible with WDM-PON architecture. (b) Schematic of pulse shaping in one channel and the resulted optical spectrum. LD: laser diode; PM: phase modulator; SMF: single-mode fiber; PC: polarization controller; FP: Fabry–Pérot; PD: photodetector; Amp: electrical amplifier; LO: local oscillator; LPF: low pass filter; BERT: bit-error-rate tester.

In this letter, we propose and demonstrate a novel UWB over fiber system that is compatible with WDM-PON architecture using a Fabry–Pérot laser diode (FP-LD). The FP-LD can be placed at the center office to serve as a multiwavelength UWB pulse shaper, or at an optical network unit (ONU) to alternately work as a pulse shaper for the downstream signal and a signal generator for the upstream signal. An experiment is performed with the transmission performance being experimentally evaluated by measuring the eye diagrams and bit-error rates (BERs). An error-free operation is achieved. The power penalty for the transmission over a 20-km single-mode fiber (SMF) is less than 3.2 dB.

II. Experimental Setup and Principle

The schematic of the proposed UWB over fiber system is shown in Fig. 1. A light wave from a laser diode (LD) is sent

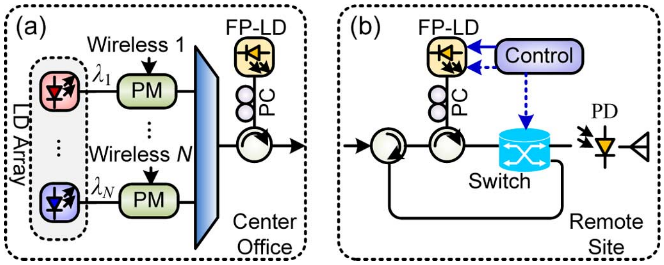

Fig. 2. Two ways to incorporate the proposed UWB over fiber system into a WDM-PON architecture. (a) FP-LD is placed at the center office; (b) FP-LD is placed at the remote site.

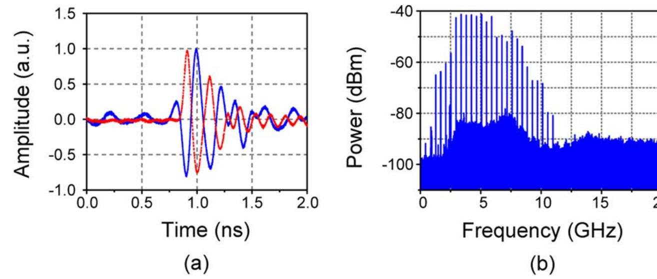

Fig. 3. Waveform and electrical spectrum of the generated UWB pulses.

to a $LiNbO_3$ phase modulator (PM). A 1.69-Gb/s signal generated by a BER tester (BERT: Agilent 4901B) with a fixed pattern "1000 0000" to represent 1 bit and "0000 0000" to represent 0 bit, is applied to the PM to phase modulate the light wave. The pulse for "1" has a shape close to a Gaussian with a full-width at half-maximum (FWHM) of about 63 ps. After transmitting through a section of SMF, the signal is sent to an FP-LD (Thorlabs S1FC1550) via a polarization controller (PC) and a circulator. The FP-LD is biased with an injection current below the threshold ($\sim$20 mA) such that the FP-LD is operating as an active optical filter. The optical carrier of the injected optical signal is located at one of the slopes of the filter, as shown in Fig. 1. Since the UWB pulses can be obtained based on phase-modulation to intensity-modulation (PM-IM) conversion at an optical filter, the input signal would be shaped to an optical on–off keying (OOK) UWB signal [2]. The UWB signal from the FP-LD is then detected by a photodetector (PD) and radiated to free space through a UWB omni-directional antenna (Skycross SMT-3TO10M-A). To evaluate the transmission performance, a UWB receiver is built. The radiated UWB signal is collected by another UWB antenna, amplified by a wideband electrical amplifier [(EA) 25-dB gain], and then mixed at an electrical mixer with a local oscillator (LO) signal at 3.38, 5.06, 6.75, or 8.44 GHz followed by a low-pass filter [(LPF) 3-dB bandwidth of 1.20 GHz], to down-convert the data signal from a center frequency of about 3.38, 5.06, 6.75, or 8.44 GHz to the baseband. Due to the limited gain provided by the EA, the antennas are placed in their peak radiation direction in the azimuth plane with a distance of 5 cm. At the output of the low-pass filter, the received baseband signal is sent back to the BERT for BER measurement. The use of an FP-LD as an active optical filter has several advantages. First, an FP-LD can support multiwavelength operation thanks to the wide gain bandwidth and the close mode spacing [11], [12]. If the FP-LD is designed to have longitudinal modes that fit the ITU grid, it can be used to simultaneously shape Gaussian pulses in multiple WDM channels to UWB pulses. Typically, the 3-dB gain bandwidth of the semiconductor gain medium in an FP-LD is larger than 20 nm, so an FP-LD can possibly support simultaneously more than 20-channel pulse shaping if a 0.8-nm channel spacing is used. Second, an FP-LD can work in the injection-locking mode. If an FP-LD is injection locked, it will lase at the same wavelength as the injected signal with the original data largely suppressed. Thus, it allows the reuse of the wavelength by directly modulating the wavelength by a new data signal [13]. For this case, the FP-LD must be biased to have an injection current above the threshold current. As a result, there are two ways to incorporate the proposed UWB over fiber system into a WDM-PON architecture, as shown in Fig. 2: 1) placing the FP-LD at the center office, it can simultaneously shape multiwavelength phase-modulated signals to UWB signals; 2) placing the FP-LD in an ONU. In this case, the phase-modulated WDM signals from the center office are divided and sent to each ONU in the remote site. By properly switching the drive current, the FP-LD can be alternately used as a UWB pulse shaper for the downstream phase-modulated signal and a signal generator for the upstream signal. In addition, by controlling the drive current of the FP-LD, an optimal frequency response can be achieved to produce a power-efficient UWB signal that fits well the spectral mask specified by the FCC.

III. Results and Discussion

An experiment is performed to demonstrate the proposed UWB over fiber system. The optical carrier of the phase-modulated injection optical signal is tuned to generate a UWB signal that has a spectrum meeting the FCC-specified spectral mask, which is located about 0.05 nm away from the peak of one longitudinal mode of the FP-LD. The inset in Fig. 1 shows the optical spectrum at the output of the FP-LD. Since the optical carrier is located at the left slope of the gain spectrum of the FP-LD, the power at the right part is greater than that at the left part. Correspondingly, an optical UWB pulse with a shape close to a Gaussian doublet is generated, as shown in Fig. 3(a). By locating the optical carrier at the right slope, the polarity of the generated Gaussian doublet is inverted, which is shown as a dashed line in Fig. 3(a). Fig. 3(b) shows the corresponding spectrum, which gives a central frequency of 5.4 GHz and a 10-dB bandwidth of about 5.5 GHz, corresponding to a fractional bandwidth of about 102%. It should be noted that the repetition rate of the UWB pulse is set at 0.42 GHz when measuring the spectrum shown in Fig. 3(b). The 0.42-GHz electrical drive signal is generated by a BERT using one "1" in every 32 bits to represent a Gaussian pulse.

The performance of the UWB over fiber system is evaluated. Fig. 4 shows the eye diagrams and the electrical spectra of the UWB signal before and after 20-km SMF transmission. In this case, the bit rate of the UWB signal is 1.69 Gb/s. Due to the fiber dispersion, the eye diagram is degraded after transmission, but the degradation is small. Since it is an OOK signal, the electrical spectra consist of both continuous and discrete components [7]. The FCC-specified indoor spectral mask is also plotted for comparison. It can be seen that the UWB signals without and with SMF transmission both fit well the FCC-specified spectral mask. In addition, the continuous spectral components, which contain the data information in the UWB signal,

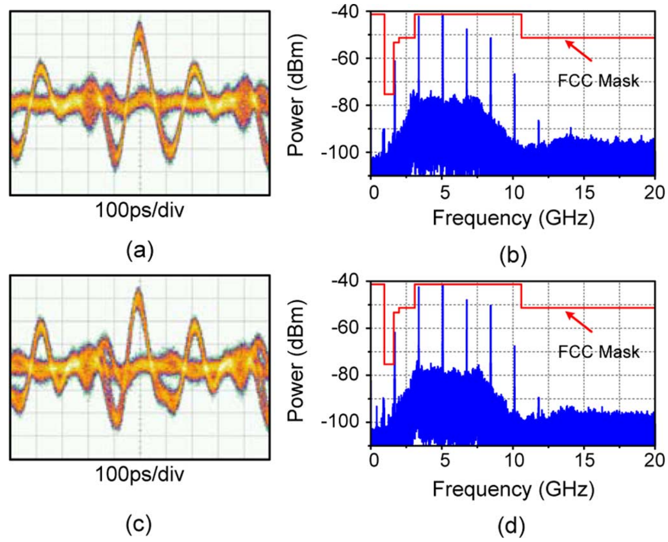

Fig. 4. Eye diagrams and electrical spectra of the UWB signals. (a), (b) Back-to-back; (c), (d) after 20-km SMF transmission.

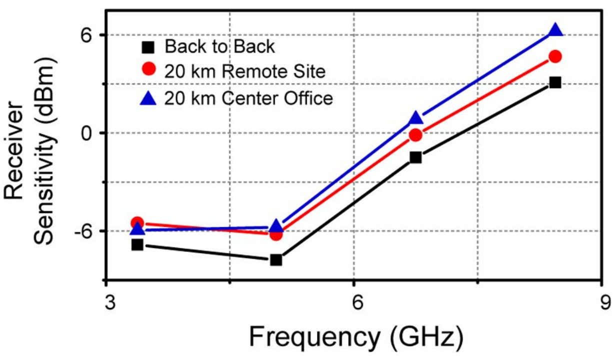

Fig. 5. Receiver sensitivity of the UWB signal at center frequencies of 3.38, 5.06, 6.75, and 8.44 GHz.

are not seriously affected by the fiber transmission, indicating that the power penalty resulted from the transmission is low.

Fig. 5 shows the receiver sensitivities of the UWB signals at center frequencies of 3.38, 5.06, 6.75, and 8.44 GHz. The receiver sensitivity is defined as the optical power required to ensure a BER of 10^{-9} at the UWB receiver. As can be seen from Fig. 5, the power penalties are all less than 1.6 dB. Since the major power of the UWB signal is distributed around these spectral components, we can conclude that the power penalty of the 20-km SMF transmission of the UWB signal is less than 1.6 dB, demonstrating that the information in the UWB signals is not seriously degraded by the fiber chromatic dispersion. In the above measurement, we assume that the FP-LD is placed in the remote site. In a second measurement, the FP-LD is located in the center office. The 20-km SMF is connected between the FP-LD and the PD as shown in Fig. 1. In that case, the power penalty of the fiber transmission is less than 3.2 dB. For both cases where the FP-LD is placed in the remote site and the center office, error-free operations are achieved.

The stability of the system is also investigated. Because the FP-LD is not temperature controlled, the gain spectrum of the FP-LD would drift slowly with the temperature change. Correspondingly, the waveform and the spectrum of the generated UWB pulse would change. The proposed system is allowed to operate in a room environment for a period of 30 min. In this period, the wavelength of the LD is adjusted by $\sim$0.01 nm to track the drift of the gain spectrum of the FP-LD. If a temperature-controlled FP-LD is used, the stability of the system should be greatly improved.

IV. Conclusion

A novel UWB over fiber system compatible with WDM-PON architecture was proposed and demonstrated. The key device in the system was the FP-LD, which was functioning as an active optical filter. By locating the optical carrier of the phase-modulated injection optical signal at one slope of the filter response, a UWB signal that has a power spectrum meeting the FCC-specified spectral mask was generated. The performance of the proposed system was evaluated by measuring the eye diagrams and the BERs. Error-free operation was achieved after 20-km SMF transmission for both cases where the FP-LD was placed in the center office and the base station. The proposed approach would find applications in future wired/wireless converged optical access networks.

References

[1] G. R. Aiello and G. D. Rogerson, "Ultra-wideband wireless systems," *IEEE Microw. Mag.*, vol. 4, no. 2, pp. 36–47, Jun. 2003.

[2] J. P. Yao, F. Zeng, and Q. Wang, "Photonic generation of ultrawideband signals," *J. Lightw. Technol.*, vol. 25, no. 11, pp. 3219–3235, Nov. 2007.

[3] C. M. Tan, L. C. Ong, M. L. Yee, B. Luo, and P. K. Tang, "Direct transmission of ultra wide band signals using single mode radio-over-fiber system," in *Proc. Asia-Pacific Microw. Conf. 2005 (APMC 2005)*, Dec. 2005, vol. 2, pp. 1315–1317.

[4] M. Abtahi, M. Mirshafiei, S. LaRochelle, and L. A. Rusch, "All-optical 500-Mb/s UWB transceiver: An experimental demonstration," *J. Lightw. Technol.*, vol. 26, no. 15, pp. 2795–2802, Aug. 1, 2008.

[5] T. B. Gibbon, X. B. Yu, R. Gamatham, N. G. Gonzalez, R. Rodes, J. B. Jensen, A. Caballero, and I. T. Monroy, "3.125 Gb/s impulse radio ultra-wideband photonic generation and distribution over a 50 km fiber with wireless transmission," *IEEE Microw. Wireless Compon. Lett.*, vol. 20, no. 2, pp. 127–129, Feb. 2010.

[6] C. W. Chow, F. M. Kuo, J. W. Shi, C. H. Yeh, Y. F. Wu, C. H. Wang, Y. T. Li, and C. L. Pan, "100 GHz ultra-wideband (UWB) fiber-to-the-antenna (FTTA) system for in-building and in-home networks," *Opt. Express*, vol. 18, no. 2, pp. 473–478, Jan. 2010.

[7] S. Pan and J. P. Yao, "UWB over fibre communications: Modulation and transmission," *J. Lightw. Technol.*, vol. 28, no. 16, pp. 2445–2455, Aug. 2010.

[8] K. Prince, J. B. Jensen, A. Caballero, X. B. Yu, T. B. Gibbon, D. Zibar, N. Guerrero, A. V. Osadchiy, and I. T. Monroy, "Converged wireline and wireless access over a 78-km deployed fiber long-reach WDM PON," *IEEE Photon. Technol. Lett.*, vol. 21, no. 17, pp. 1274–1276, Sep. 1, 2009.

[9] R. Llorente, T. Alves, M. Morant, M. Beltran, J. Perez, A. Cartaxo, and J. Marti, "Ultra-wideband radio signals distribution in FTTH networks," *IEEE Photon. Technol. Lett.*, vol. 20, no. 11, pp. 945–947, Jun. 1, 2008.

[10] K. Grobe and J. P. Elbers, "PON in adolescence: From TDMA to WDM-PON," *IEEE Commun. Mag.*, vol. 46, no. 1, pp. 26–34, Jan. 2008.

[11] H. D. Kim, S. G. Kang, and C. H. Lee, "A low-cost WDM source with an ASE injected Fabry–Pérot semiconductor laser," *IEEE Photon. Technol. Lett.*, vol. 12, no. 8, pp. 1067–1069, Aug. 2000.

[12] T. T. Pham, H. S. Kim, Y. Y. Won, and S. K. Han, "Bidirectional 1.25-Gbps wired/wireless optical transmission based on single sideband carriers in Fabry–Perot laser diode by multimode injection locking," *J. Lightw. Technol.*, vol. 27, no. 13, pp. 2457–2464, Jul. 1, 2009.

[13] L. Y. Chan, C. K. Chan, D. T. K. Tong, F. Tong, and L. K. Chen, "Upstream traffic transmitter using injection-locked Fabry–Perot laser diode as modulator for WDM access networks," *Electron. Lett.*, vol. 38, no. 1, pp. 43–45, Jan. 2002.