A Cost-Effective Fast Frequency-Hopped Code-Division Multiple-Access Light Source Using Self-Seeded Fabry–Pérot Laser With Fiber Bragg Grating Array

Wei-Ren Peng, Peng-Chun Peng, Wen-Piao Lin, *Member, IEEE*, Kuei-Chu Hsu, Yin-Chieh Lai, and Sien Chi

Abstract—**We propose a novel light source for the optical fast frequency-hopped code-division multiple-access scheme using a self-seeded gain-switched Fabry–Pérot laser diode (FP-LD) with the reconfigurable fiber Bragg grating array (FBGA). The embedded FBGA in the external cavity loop encodes the input pulses both temporally and spectrally. Before feeding back into the FP-LD, the encoded optical pulses propagate the FBGA with reverse direction and are again temporally combined. With the corporation of the variable fiber delay line, the limitation of the pulse rate by the fixed external cavity length is removed and makes the scheme more flexible. The output with sidemode suppression ratio of more than 20 dB has been obtained. With three fiber Bragg gratings on the FBGA, we demonstrate the encoded chip rate of 1.425 GHz under the driving radio frequency of 475 MHz. It is proved that a different codeword can be generated by simply reconfiguring the encoder without changing the rest of the experimental setup.**

Index Terms—**Fiber Bragg grating (FBG), optical fast frequency-hopped code-division multiple-access (OFFH-CDMA), self-seeded Fabry–Pérot laser diode (FP-LD).**

I. INTRODUCTION

RECENTLY, optical code-division multiple-access (OCDMA) is an attractive technology for local access networks due to its potential of allowing more subscribers with asynchronous access and distributed network management providing higher bandwidth and enhanced security. Due to the positive optical signal feature, imperfect orthogonality between codes induces large multiple-access interference (MAI) and, thus, limits the subscriber number severely. To realize CDMA in optical domain, a less MAI scheme called frequency-hopped CDMA (FH-CDMA) is more suitable. The passive optical fast frequency hopping was first developed using the fiber Bragg grating array (FBGA) in 1999 [1]. FBGA provides a cheap, compact, and extremely simple encoding/decoding module for the user end. Most experimental implementations of the OCDMA scheme to date use the free-running gain-switched Fabry–Pérot laser diode (FP-LD) or super-continuum (SC) light source for encoding [2], [3]. The free-running gain-switched FP-LD suffers mode fluctuations due to mode competitions in the laser cavity and exhibits unstable signaling, which is improper for OCDMA encoder. The SC source is really broad-band and high speed but the optical pulses generated close to transformed-limited, which might superpose coherently and, hence, is not a suited choice for incoherent encoding. Recently, a new source for incoherent encoding in OFFH-CDMA has been proposed which is a sequentially self-seeding FP-LD solving the problem of power fluctuation [4], [5]. However, additional electrical-optical modulator (EOM) for gating is required and complicates the encoder module.

In this letter, we demonstrate a simple configuration of an encoder built-in FP-LD based on the configuration of an actively mode-locked fiber laser [6]. Optical pulse trains with colors are generated after returned from the FBGA. Before injection back to the FP-LD, the encoded pulses with different colors will be combined temporally after returned from FBGA at the other end. The combined pulses will be used for seeding the FP-LD. Erbium-doped fiber amplifier (EDFA) is used not only for power compensation in the external cavity loop but also can be used for power control over network [7]. With the insertion of variable fiber delay line (VFDL) in the cavity loop, we can change the operation bit rate flexibly without considering the fundamental frequency of the external cavity. In this scheme, there is no need for the frequency divider and the additional EOM used for gating compared to the previous one [4], [5], it is more cost-effective and simple to construct. In addition, our coding module can sustain the same bit rate as the radio frequency (RF) injected into the FP-LD.

II. SYSTEM DESCRIPTION

The schematic diagram of the proposed coding scheme is shown in Fig. 1, which consists of an RF synthesizer, an FP-LD, a polarization controller (PC), three optical circulators (OC1, OC2, OC3), an FBGA, an EDFA, an output coupler, and the VFDL. An external fiber cavity is constructed for providing feedback to the FP-LD [5]. The optical path in the external cavity is $\mathrm{FP-LD} \rightarrow \mathrm{PC} \rightarrow \mathrm{OC1\ port\ 3} \rightarrow \mathrm{OC2\ port\ 2} \rightarrow \mathrm{FBGA} \rightarrow \mathrm{OC\ 2\ port\ 3} \rightarrow \mathrm{EDFA} \rightarrow \mathrm{OC\ 3\ port\ 2} \rightarrow \mathrm{FBGA} \rightarrow \mathrm{OC\ 3\ port\ 3} \rightarrow \mathrm{VFDL} \rightarrow \mathrm{OC\ 1\ port\ 2} \rightarrow \mathrm{PC} \rightarrow \mathrm{FP-LD}$. The PC is used to adjust the polarization state of the

---

Manuscript received March 31, 2004; revised July 1, 2004. This work was supported in part by the MediaTek Fellowship and in part by the National Science Council of R.O.C. under Contracts NSC-92-2215-E-009-008, NSC 93-2752-E-009-009-PAE, and NSC 93-2215-E-155-005.

W. R. Peng, P. C. Peng, K. C. Hsu, and Y. C. Lai are with the Institute of Electro-Optical Engineering, National Chiao-Tung University, Hsinchu 300, Taiwan, R.O.C. (e-mail: pwz@aieo.idv.tw).

W. P. Lin is with the Department of Electrical Engineering, Chang Gung University, Tao Yunan 333, Taiwan, R.O.C.

S. Chi is with the Institute of Electro-Optical Engineering, National Chiao-Tung University, Hsinchu 300, Taiwan, R.O.C., and also with the Institute of Electro-Optical Engineering, Yuan Ze University, Chungli 320, Taiwan, R.O.C.

Digital Object Identifier 10.1109/LPT.2004.835615

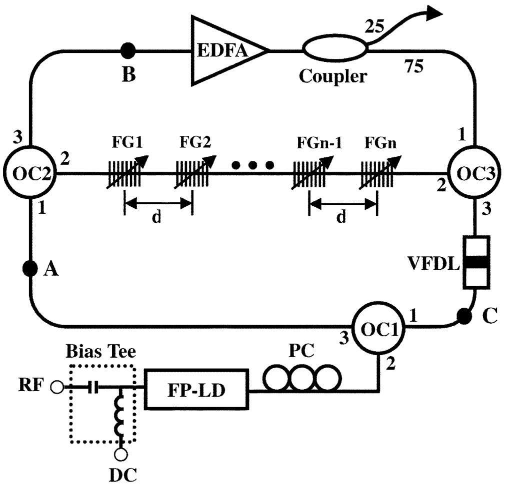

Fig. 1. Experimental setup of the proposed FFH-CDMA coding module.

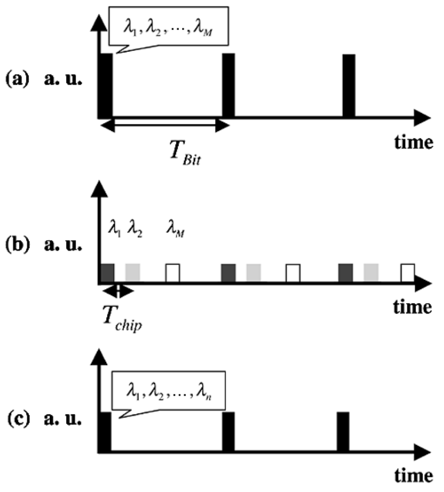

Fig. 2. Signals at the loop positions of A, B, and C, respectively.

light injected to the LD for the best modulation. The embedded FBGA are used to encode the input pulses temporally and spectrally and to recombine the encoded chips before seeding back to the FP-LD for modes lasing. The total cavity length for any optical pulse reflected from the corresponding FBG is the same. EDFA and VFDL are used for power compensation in external cavity loop and the timing of the feedback pulse train, respectively.

Fig. 2(a)–(c) shows the working principle of our proposed scheme. The RF synthesizer drives the FP-LD to emit the free-running pulse trains, which are shown in Fig. 2(a). Each pulse is with multiple longitudinal modes $(\lambda_1, \lambda_2, \lambda_3, \lambda_4, \ldots, \lambda_M)$ of the FP-LD and the pulse repetition rate is $f = 1/T_{\rm bit}$. After being reflected from the FBGA of n FBG sections, the optical pulse train is with the hop pattern of $(\lambda_1, \lambda_2, \lambda_3, \ldots, \lambda_n)$, shown in Fig. 2(b). The chip duration is equal to the round-trip time between adjacent gratings $T_{\rm chip} = 2d/v$, where d and v are the grating spacing and optical velocity in fiber, respectively. The encoded pulses will be partially coupled to output for data modulation through a branch of the coupler. Through the other branch of the coupler, the encoded pulses will be recombined through the decoding process of the FBGA. Each pulse is with n wavelengths of $(\lambda_1, \lambda_2, \sim, \lambda_n)$ and the pulse duration of $T_{\rm bit}$. For efficient seeding, the modulation RF should be the harmonics of the fundamental frequency of the external cavity length [5].

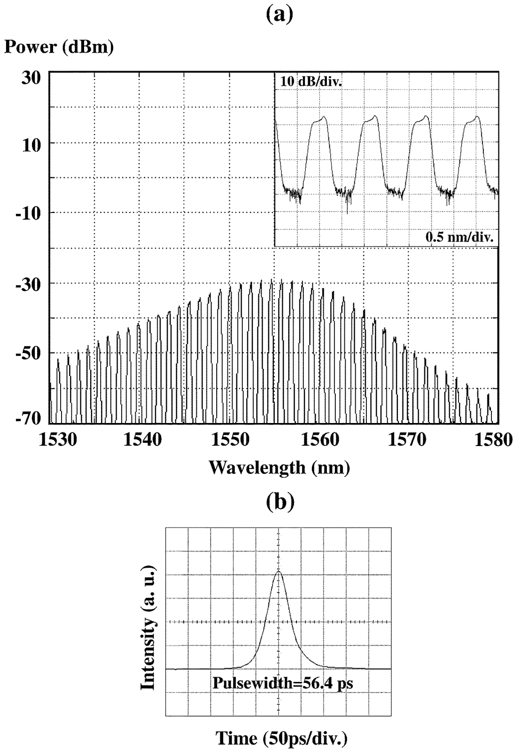

Fig. 3. (a) Optical spectrum of the FP-LD. The inset shows the detail view of the center wavelength. (b) Detailed pulse information with width of about 56.4 ps.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The optical source is a commercial FP-LD operating at 1555 nm. The mode spacing and the continuous-wave lasing threshold are 1.08 nm and 10.1 mA, respectively. The FP-LD is biased at 5.6 mA and the temperature was set at 23 °C. It is gain-switched with an RF signal at $f_{\rm RF} = 475$ MHz. The spectrum and the corresponding pulse shape of the FP-LD are shown in Fig. 3(a) and (b), respectively. The inset in Fig. 3(a) shows the detailed view near the center wavelength. Fig. 3(b) shows the width of the output pulse is about 56.4 ps, which is narrow enough for high-speed coding. The FBGA we used contains three FBGs for coding. The FBGs are fabricated by the masking method and with $d = 5$ cm spacing between gratings for mechanically tunning. Each FBG is with a bandwidth of 0.4 nm and reflectivity of over 99%. Fig. 4 shows the spectra and the encoded pulse sequence from the coupler (25 : 75) output after self-seeding. Three FP-LD longitudinal modes at $\lambda_1 = 1548.82$ nm, $\lambda_2 = 1549.9$ nm, and $\lambda_3 = 1550.98$ nm are coded by the FBGA and the sidemode suppression ratio (SMSR) more than 20 dB is obtained. The observed sequences are with bit duration of about $T_{\rm bit} \approx 2.1$ ns and chip duration of about $T_{\rm chip} \approx 500$ ps, which are matched the designed value of RF $f_{\rm RF} = 475$ MHz and the grating spacing $d = 5$ cm, respectively. To demonstrate the other possibility of codeword, λ_3 is shifted to $\lambda_4 = 1552.06$ nm by tunning the corresponding grating while the other two modes $\lambda_1 = 1549.9$ nm and $\lambda_2 = 1548.82$ nm are not changed. Their results are shown

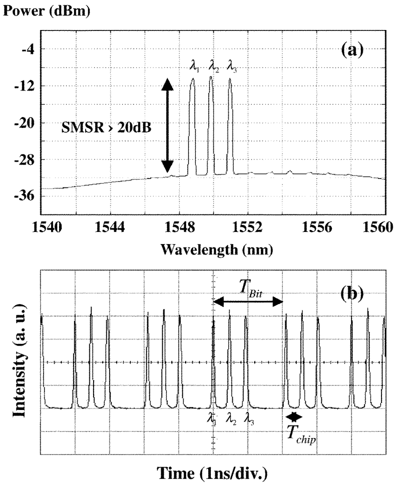

Fig. 4. (a) Encoded signal output spectrum after self-seeded, where $\lambda_1 = 1548.82$ nm, $\lambda_2 = 1549.9$ nm, and $\lambda_3 = 1550.98$ nm. (b) Encoded signal with bit and chip durations of 2.1 ns and 500 ps, respectively. The sequence order in time domain is $\lambda_1 \rightarrow \lambda_2 \rightarrow \lambda_3$.

in Fig. 5. The SMSR with more than 20 dB is obtained. We continuously monitor the three wavelengths for 10 min. Power variation of lasing wavelengths is less than 0.4 dB. The power variation increases if the polarization of this system is unstable. According to the self-seeded mechanism [8], only one polarization direction of the feedback light results in the maximum self-seeded efficiency.

The role of EDFA is not only for power compensation for the loss of the fiber cavity loop, but also can be used for power control over network. The signal output power will be controlled by the network manager and it can improve the system performance and efficiency [7]. Since the data bit rate governed by the RF should be harmonics of the fundamental frequency of the external cavity, it can be any specific value by adjusting the cavity length through the VFDL. The fundamental frequency of system is about 5 MHz, and the cavity length is about 41.38 m. The required cavity length can be flexibly achieved by the VFDL in the system. The only constraint on the RF frequency is to avoid adjacent bit aliasing after encoding, for less MAI in networking [1]. For our case, the RF frequency is upper bounded by $f_{\mathrm{RF}} \leq 1/3T_{\mathrm{chip}} = 667$ MHz. The usable wavelength number is limited by the FBGA total length. Using the multipassband chirped Moiré grating instead, the overall FBGA length can be reduced or more wavelengths can be supported [9]. The tuning range is decided by the FBG tunability and the FP-LD output power. A laser diode with a higher output power over a broad spectral range can enhance the wavelength tuning. The SMSR can be further improved by applying antireflection coating on the diode facet to suppress amplified spontaneous emission of the nonselected cavity mode. In addition, two-dimensional coding is possible by tuning the FBGA properly.

IV. CONCLUSION

We have proposed a novel and simple OFFH-CDMA coding module using self-seeded gain-switched FP-LD with embedded FBGA. We remove the EOM required for gating and its corresponding complex timing and controlling compared to the previous scheme [4], [5]. With the tunability of the FBGs in FBGA, we can dynamically change the address code for data destination. We demonstrate the scheme by driving 475-MHz RF frequency to the FP-LD and encoded pulse streams with chip rate of 1.425 GHz. We also demonstrate the possibility of other codeword with different encoded wavelengths. The SMSR of larger than 20 dB is obtained in the two cases and unstable mode competition does not exist. The experimental results show that the demonstrated codewords are with small power variance between chips, which makes the coding module practical. Finally, the coding module can also be used for two-dimensional OCDMA coding if we insert different optical paths between gratings in FBGA. In addition, a light source of frequency-encode CDMA is also possible if the output is from the Port 3 of OC3.

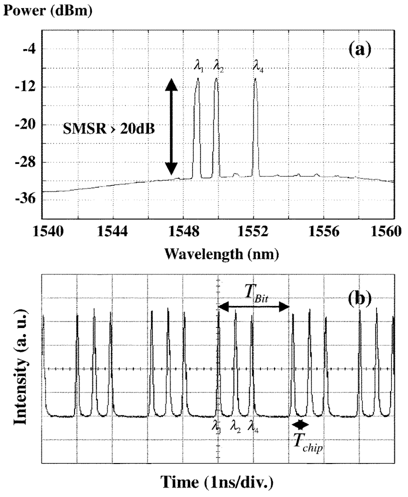

Fig. 5. (a) Encoded signal output spectrum after self-seeded, where $\lambda_1 = 1548.82$ nm, $\lambda_2 = 1549.9$ nm, and $\lambda_4 = 1552.06$ nm. (b) Encoded signal with bit and chip durations of 2.1 ns and 500 ps, respectively. The sequence order in time domain is $\lambda_1 \rightarrow \lambda_2 \rightarrow \lambda_4$.

REFERENCES

[1] H. Fathallah, L. Rusch, and S. Larochelle, "Passive optical fast frequency-hop CDMA communications system," *J. Lightwave Technol.*, vol. 12, pp. 397–405, Mar. 1999.

[2] X. Wang, K. T. Chan, Y. Liu, L. Zhang, and I. Bennion, "Novel temporal/spectral coding technique based on fiber Bragg gratings for fiber optic CDMA application," in *Dig. OFC/IOOC'99*, 1999, Paper WM50, pp. 341–343.

[3] N. Wada, H. Sotobayashi, and K. Kitayama, "2.5 Gbit/s time-spread/wavelength-hop optical code division multiplexing using fiber Bragg grating with super-continuum light source," *Electron. Lett.*, vol. 36, pp. 815–817, 2000.

[4] X. Wang, K. L. Lee, C. Shu, and K. T. Chan, "Multiwavelength self-seeded Fabry–Pérot laser with subharmonic pulse-gating for two-dimensional fiber-optic CDMA," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 1361–1363, Dec. 2001.

[5] X. Wang and K. T. Chan, "A sequentially self-seeded Fabry–Pérot laser for two-dimensional encoding/decoding optical pulse," *IEEE J. Quantum Electron.*, vol. 39, pp. 83–90, Jan. 2003.

[6] S. Li and K. T. Chan, "A novel configuration for multiwavelength actively mode-locked fiber lasers using cascaded fiber Bragg gratings," *IEEE Photon. Technol. Lett.*, vol. 11, pp. 179–181, Feb. 1999.

[7] E. Inaty, H. M. H. Shalaby, P. Fortier, and L. A. Rusch, "Multirate optical fast frequency hopping CDMA system using power control," *J. Lightwave Technol.*, vol. 20, pp. 166–177, Feb. 2002.

[8] M. Schell, D. Huhse, W. Utz, J. Kaessner, D. Bimberg, and I. S. Taraov, "Jitter and dynamics of self-seeded Fabry–Pérot laser diodes," *IEEE J. Select. Topics Quantum Electron.*, vol. 1, pp. 528–534, June 1995.

[9] L. R. Chen and P. W. E. Smith, "Demonstration of incoherent wavelength-encoding/time-spreading optical CDMA using chirped Moire gratings," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 1281–1283, Sept. 2000.