Phase Encoding and Decoding of Short Pulses at 10 Gb/s Using Superstructured Fiber Bragg Gratings

P. C. Teh, P. Petropoulos, M. Ibsen, and D. J. Richardson

***Abstract*—A 7-chip, 160-Gchip/s phase-shift keyed code is assigned to short pulses after reflection from a superstructured fiber Bragg grating. The code is then recognized by a second grating, which is nominally identical to the encoder grating. Such an encoding/decoding action is required in code-division multiple-access systems and packet-switched networks.**

***Index Terms*—Bragg grating, fiber-optic communication, optical bipolar code, optical code-division multiplexing.**

I. Introduction

OPTICAL code division multiple access (OCDMA) has recently attracted significant interest as an alternative transmission scheme for applications that require higher privacy levels, asynchronous operation, more flexible bandwidth management, and potential for higher connectivity. Its operation relies on assigning to each user particular waveforms (codes), each code corresponding to one data symbol. The codes are transmitted and decoded at the intended receiver end by matched filtering. Thus, simultaneous transmission of several users over the same wavelength allocation is possible. However, the problem of generating (and recognizing) appropriately coded optical signals is not trivial. Synthesis of the codes using electrooptic modulation is possible but not desirable due to the bandwidth limitations associated with the modulators, which would necessarily restrict the effective transmission rate to relatively low values; moreover, it would be expensive. All-optical solutions are thus required and, indeed, several have been suggested and demonstrated. These include the use of optical delay lines [1]–[3], phase encoding in the wavelength domain using arrayed waveguide gratings [4], and spatial modulation of light in a $4f$ pulse-shaping system [5].

Fiber Bragg gratings (FBGs) constitute passive spectral filters and can be used for the same purpose, offering at the same time significant advantages over the aforementioned alternatives, such as ready integrability with fiberized systems, compactness, and low fabrication cost. Moiré FBGs [6] or arrays of uniform FBGs [7] have been suggested for wavelength encoding of pulses (frequency-hopping CDMA) and the approach has been demonstrated experimentally. Moreover, it is also possible to use fiber gratings for pulse encoding in the time domain as required for direct-sequence CDMA [8], [9]. We have focused our attention on the use of superstructured fiber Bragg gratings (SSFBGs) for this purpose [10]. SSFBGs are single-grating structures having a slowly varying amplitude and/or phase pattern (superstructure) imposed upon a uniform background refractive index modulation. In the weak grating limit, (reflectivity $R < 20\%$), the shape of the impulse response directly follows the shape of the spatial superstructure. Thus, CDMA codes can be written directly into the SSFBG, such that short pulses reflected from the structure are shaped into the codewords. Pattern recognition can be achieved by the inverse process [11]. We have previously validated the SSFBG approach in a proof-of-principle experiment operating using 7-chip unipolar code sequences, with a chip duration of 235 ps and a data rate of 125 MHz [8].

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II. Experiment

In the work described herein, we investigate the possibility of using the SSFBG technique to implement codewords with chips of much shorter duration, as required in high-bit-rate systems. We experimentally demonstrate bipolar (phase-shift-keyed) pulse encoding and decoding at a data rate of 10 Gb/s, using 7-chip codes, with a chip duration of 6.4 ps (resulting in an aggregate codeword duration of 44.8 ps and a chip rate of 160 Gchip/s).

Our experimental setup is shown in Fig. 1. The primary pulse source was an actively and harmonically mode-locked erbium fiber ring laser (EFRL), which delivered ~2-ps soliton pulses at a repetition rate of 10 GHz. The pulses were modulated at 10 Gb/s using a $2^{31} - 1$ pseudorandom bit sequence and fed to the encoder SSFBG by means of an optical circulator. The encoded sequence was subsequently decoded using a second SSFBG, which was matched to the encoder grating. The resulting code-correlation pulse was then detected using either a 10 Gb/s receiver or second harmonic generation (SHG) autocorrelator. Note that we performed experiments with either back-to-back encoding : decoding, or after propagation of the encoded signal over a 25-km-long standard fiber transmission line, incorporating a linearly chirped FBG (LCFBG) to compensate for the fiber's dispersion.

The specific code that we used was the 7-chip binary m-sequence 1 110 010. Each of the SSFBGs was 4.64 mm long and each chip in the SSFBG structures was $L_{\rm chip} = 0.66$ mm long, corresponding to a chip duration of $\tau_{\rm chip} = 2nL_{\rm chip} = 6.4$ ps (i.e., a chip rate of 160 Gb/s). Note that this is just over three times the length of the input pulses, thereby ensuring that the code sequences generated closely followed the form of the idealized impulse response.

The SSFBGs were written using the continuous grating writing technique [12]. This technique allows flexible tailoring

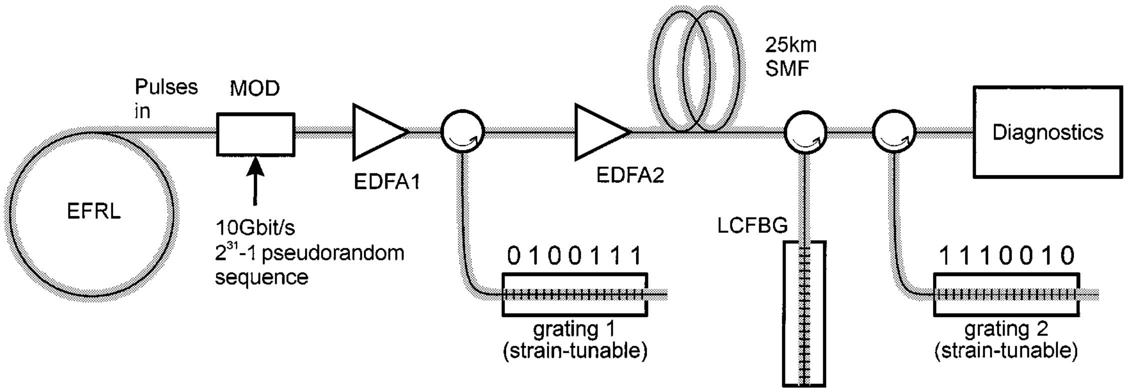

Fig. 1. Experimental setup (MOD: $LiNbO_3$ electrooptic modulator; EDFA: Erbium-doped fiber amplifier; SMF: single-mode fiber).

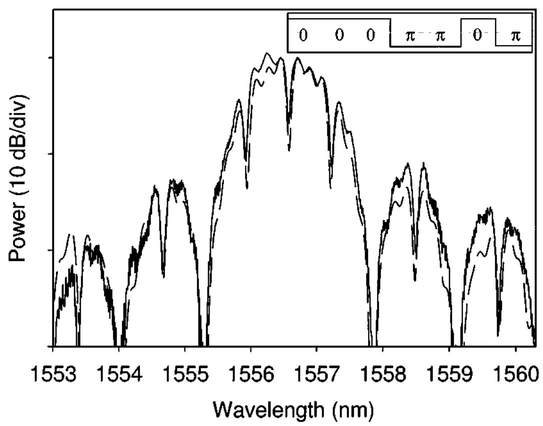

Fig. 2. Spectral response of the 7-chip 160 Gchip/s bipolar encoding SSFBG (solid line: measured response, dashed line: designed response). Inset: bipolar code.

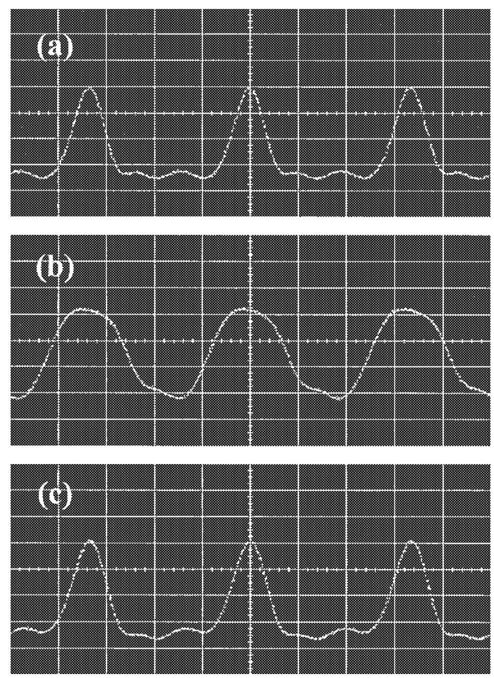

Fig. 3. Oscilloscope traces of (a) incoming 2-ps pulse stream (b) encoded pulses, and (c) decoded pulses (detection bandwidth: ∼20 GHz–30 ps/div).

of the FBG amplitude and phase characteristics, as the gratings are written plane by plane; hence, there is no need for specially patterned phase masks. The technique is not limited by the inherent imperfection associated with the fabrication of long phase masks and allows for excellent control along considerably longer grating structures than described here. The bipolar code was implemented by introducing distinct π phase shifts into the refractive index modulation profile of the SSFBGs, distributed as defined by our choice of m-sequence code (see inset of Fig. 2). The measured spectral response of the SSFBGs is shown in Fig. 2 along with the design response. The decode SSFBG was identical to the encoder other than that the modulation profile was spatially reversed relative to the encoder to provide the temporally inverted impulse response.

A trace of the encoded waveform is shown in Fig. 3(b), obtained using a fast photodiode and a sampling oscilloscope (aggregate bandwidth: ∼20 GHz). Obviously, the phase characteristics of the encoded waveform cannot be detected under square-law detection; however, reshaping of the initial pulses [Fig. 3(a)] to a pattern of a similar duration to that of the design code is clearly observed. Unfortunately, the restricted bandwidth of our measurement system means that we cannot directly resolve the individual chips within the code. However, the fact that the encoded pattern appears flat topped is an indication that the whole SSFBG structure contributes equally to the reflection of the incoming pulse as required from our weak-grating design limit. A comparison between the obtained SHG-autocorrelation signal and that theoretically calculated gives a further insight on the quality of the encoded waveform [Fig. 4(a)]. Note that the reflectivity of the gratings was ∼50%, greater than the normally accepted weak grating design limit and almost an order of magnitude stronger than the gratings used in earlier experiments [8], [9].

The encoded pattern was decoded using the matched SSFBG. Both SSFBGs were strain-tuned in order to finely match their operating wavelengths. The corresponding oscilloscope trace for the decoded pulses is presented in Fig. 3(c), which clearly shows that short, distinct pulses are reformed. We examined the decoded pulses using the SHG intensity autocorrelator, in order to assess the duration of the resultant correlation signal. The trace we obtained is shown in Fig. 4(b) and is compared to the theoretical intensity autocorrelation function of the decoder response to the incident code pattern for an initial 2-ps soliton pulse input. The agreement between the two traces is seen to be excellent. Note, the slight background that extends

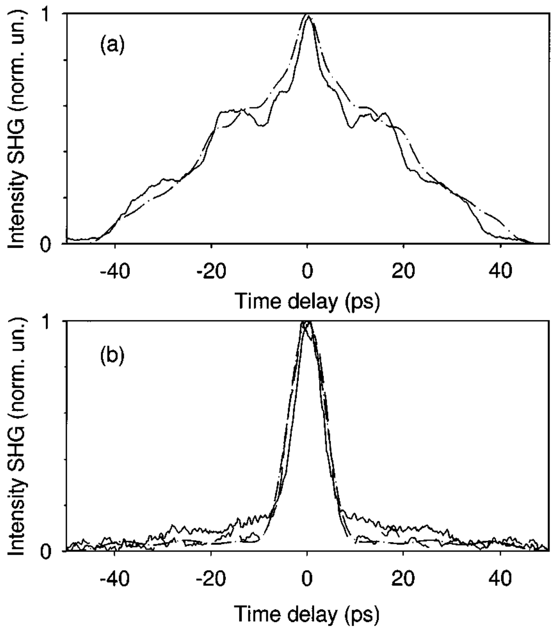

Fig. 4. Intensity autocorrelation functions of (a) the encoded waveforms, and (b) the decoded signals before (dashed line) and after transmission (solid line); the theoretical intensity autocorrelation traces are also shown (dash–dot lines).

up to $\sim \pm 40$ ps away from the main peak is actually part of the decoded signal, the total duration of which is nominally twice that of the code, i.e., 89.6 ps.

We transmitted the codes over the 25-km-long dispersion-compensated transmission line. An intensity autocorrelation trace of the decoded signal in this instance is also shown in Fig. 4(b). There is evidence of some signal degradation in terms of the background suppression; however, the effect is very small. Nevertheless, one should appreciate the stringent requirements imposed on the dispersion compensation in this case, since the aggregate transmission rate is 160 Gb/s as dictated by the chip rate.

We performed bit-error-rate (BER) measurements on the decoded signal, both with and without transmission. The results are summarized in Fig. 5. Clear eye diagrams were obtained, and there was virtually no power penalty associated with the transmission.

III. Conclusion

We have demonstrated pulse encoding and decoding at a data rate of 10 Gb/s using SSFBGs. The code we used was a 7-chip-long phase-shift keyed pseudorandom sequence with a chip rate of 160 Gchip/s. We believe this technique offers tremendous possibilities for practical passive pattern generation/recognition, as required in OCDMA systems and packet-switched networks [13]. Any practical system will, of course, require longer codes in order to accommodate more users, and we are currently actively investigating this issue.

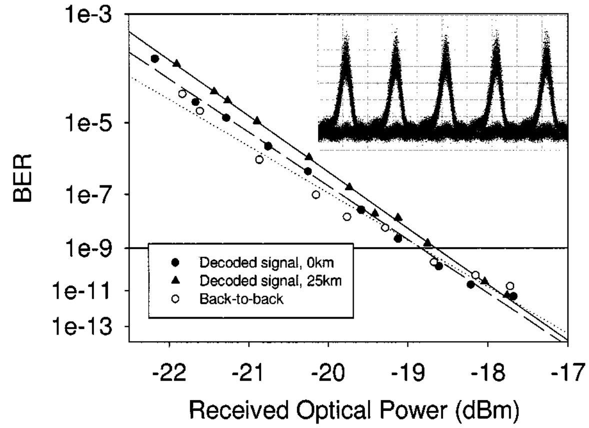

Fig. 5. BER measurements of the decoded signal before and after transmission. Inset: Eye diagram of the decoded signal after transmission.

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