Demonstration of a Four-Channel WDM/OCDMA System Using 255-Chip 320-Gchip/s Quarternary Phase Coding Gratings

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

***Abstract*—In this letter, we report the fabrication and application of 255-chip 320 Gchip/s quaternary phase superstructure fiber Bragg gratings (SSFBGs) for optical code generation and recognition in a four-channel wavelength-division-multiplexing (WDM)/optical code-division-multiplexing (OCDM) experiment. Individual users of the system operate with different coding schemes, repetition rates, and wavelengths. Our experiments show that a single SSFBG can be used to perform simultaneous optical decoding and wavelength channel selection.**

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

I. INTRODUCTION

THE CONCEPT OF code division multiple access (CDMA) has been implemented with great success in wireless communications and is now becoming of growing interest for application in optical access networks. Optical code division multiple access (OCDMA) promises a variety of attractive features for network operators relative to the more conventional wavelength-division multiplexing (WDM)/optical time-division multiplexing (OTDM) and associated optical access techniques. These features include the following amongst others: enhanced network scalability, asynchronous operation, flexible bandwidth management, improved security, and the potential for higher levels of connectivity. The OCDMA is a spread-spectrum broadcast technique in which each user of the network is allocated a unique optical code (address). This code can be used to label data bits broadcast onto the network that are intended for receipt by a particular user, or alternatively to label bits that have been sent from a particular user.

Recently, superstructured fiber Bragg grating (SSFBG) technology has emerged as an attractive and highly flexible route to produce high performance, and potentially low cost, code generation, and recognition components. An SSFBG has a rapidly varying refractive index modulation (of uniform amplitude and pitch), onto which an additional slowly varying amplitude/phase CDMA code (superstructure) has been imposed along its length. For a weak SSFBG, (reflectivity R <20%), the shape of the impulse response follows directly the shape of the spatial superstructure. Short pulses reflected from the grating are, thus, reshaped into coded pulse sequences with the same form as the superstructure profile used to write the grating. Pattern recognition can then be obtained by matched filtering the resulting coded signal using a decoder grating with the conjugate impulse response (i.e., a grating with a spatially reversed superstructure profile relative to that of the encoder grating [1]). To date, we have demonstrated single-wavelength single/two user OCDMA experiments using SSFBGs incorporating bipolar codes of up to 63 chips in length and with chip rates as high as 160 Gchip/s [1].

In this letter, we demonstrate that our SSFBG fabrication method is scalable to longer codes (255 chips) and higher chip rates (320 Gchip/s) than previously shown. In these experiments, we demonstrate the use of quaternary phase coding in OCDMA for the first time, and show that the wavelength selectivity of gratings means that this coding/decoding approach is inherently compatible with WDM.

II. FABRICATION AND CHARACTERIZATION

All the SSFBGs used in the experiment were fabricated using our continuous grating writing technique requiring only a single uniform pitch phase mask [2]. This technique allows for excellent control of the amplitude and phase of the refractive index modulation along the grating length. Two “orthogonal” 255-chip 320 Gchip/s quaternary phase coding SSFBGs, denoted by Q1 and Q2 were fabricated. The codes used are obtained from the family $\mathcal{A}$ sequences known from mobile communications. Quaternary coding is known to provide codes with more desirable cross-correlation characteristics than can be achieved with lower level coding (i.e., the unipolar and bipolar previously demonstrated with SSFBGs) [3]. These SSFBGs provide the longest code sequences, and highest chip rates yet reported for DS-OCDMA, moreover, we believe that these are the first gratings to be reported that incorporate quaternary phase coding. In Fig. 1, we show theoretical and experimental plots of the reflectivity spectrum of grating Q1, along with the associated phase-modulation profiles of the code sequence. The quality of the grating is evident when comparing the experimental and theoretical reflectivity spectra of grating Q1. Similar quality is also obtained with grating Q2.

III. SYSTEM CHARACTERIZATION

In Fig. 2(b), we show the oscilloscope trace of the coded Q1 channel obtained by reflecting 2.5-ps short pulses [as in

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Manuscript received June 5, 2001; revised October 25, 2001.

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Publisher Item Identifier S 1041-1135(02)00490-1.

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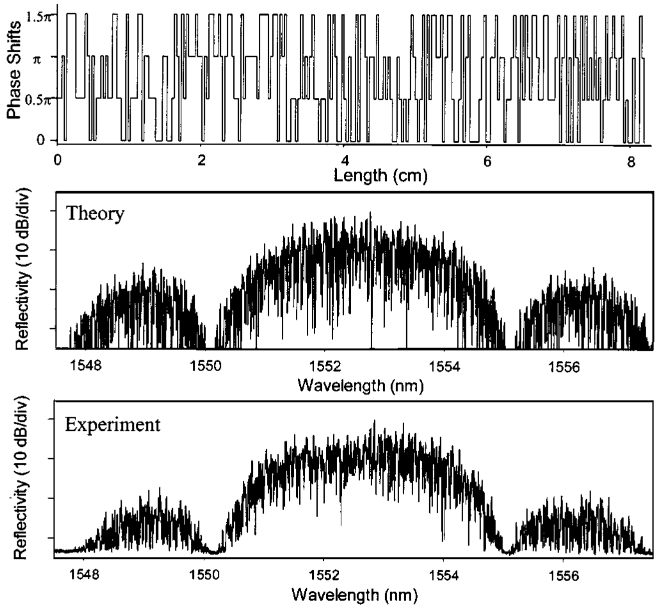

Fig. 1. Phase modulation profile, and spectral reflectivity profiles (theory and experiment) for a 255-chip 320-Gchip/s quadrature sequences SSFBG (Q1). The grating has a peak reflectivity of ~25% and is 8.44-cm long.

Fig. 2(a)] from grating Q1. Although the individual features of the coded sequence are too short to be resolved (each chip has a length of 3.2 ps and the detection system has ~20-ps resolution) it is clear that the coding grating spreads the incident 2.5-ps pulse over a time period of ~ 800 ps as expected. Fig. 2(c) shows the corresponding oscilloscope trace when grating Q2 is used for encoding. For convenience, we denote the individual matched filters to the individual codes using the notation Q1*, Q2*, where for example Q1* is the matched decoder to grating Q1. In Fig. 2(d), we plot the decoded response of grating Q1* to code sequence Q1, denoted Q1:Q1*, where it is seen that a short chip length pulse on a very low-level pedestal background is obtained, thereby providing a very high-quality pattern recognition signal. In Fig. 2(e), we plot the response Q2:Q1* (i.e., incorrect code matching). No discernible recognition signature is observed as expected for two “orthogonal” family $\mathcal{A}$ codes. Similarly, high-quality recognition signals were obtained for other combinations of the code grating pairs (e.g., Q2:Q2* and Q1:Q2*). SHG intensity autocorrelation measurements showed the recognition signal to have a well defined peak having a width of ~3.2 ps, in good agreement with our calculations.

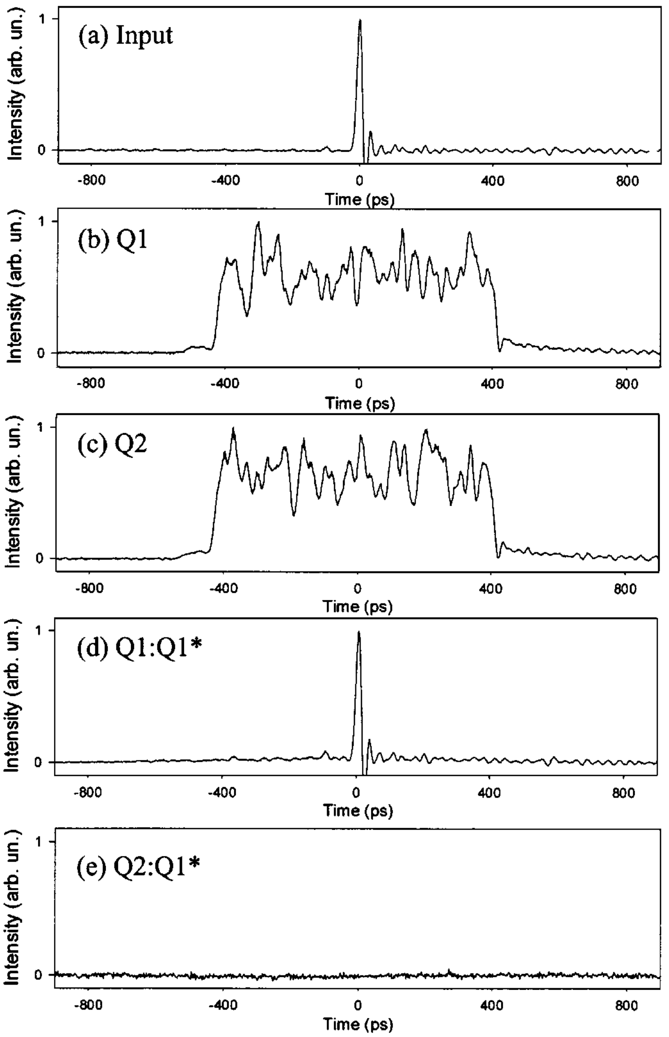

Fig. 2. Oscilloscope traces of (a) 2.5-ps soliton input pulse, (b) encoded waveform after reflection from SSFBG Q1, (c) encoded waveform after reflection from SSFBG Q2, (d) after matched filtering for the grating combinations Q1:Q1*, (e) after-matched filtering for the grating combinations Q2:Q1*. The measured resolution was ~20 ps.

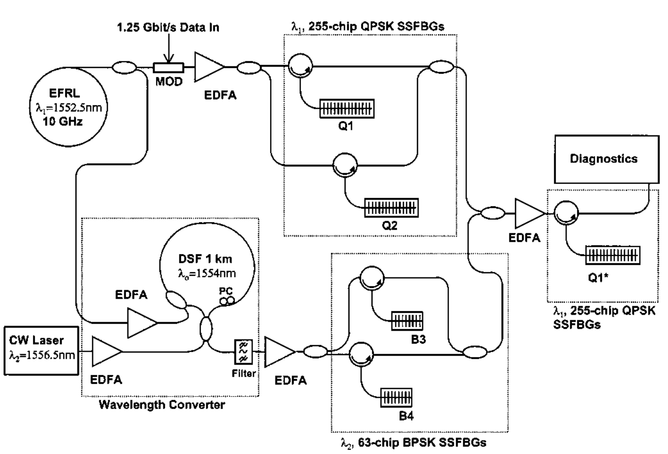

Fig. 3. Experimental setup. QPSK: Quaternary phase shift keying. BPSK: Bipolar phase shift keying.

Our experimental WDM/OCDMA setup is shown in Fig. 3. Pulses from a 2.5-ps 10-GHz regeneratively mode-locked erbium fiber ring laser (EFRL) operating at 1552.5 nm were first split using a coupler into two separate fibers. The first of these outputs was gated down to a repetition rate of 1.25 GHz and modulated to provide a 2^7-1 pseudorandom data sequence of 2.5-ps pulses at a data rate of 1.25 Gb/s. The second output was first amplified and then fed to the control port of a dual-wavelength NOLM operating as a wavelength converter (WC). The NOLM configuration allowed us to modulate the output of a continuous-wave DFB laser operating at 1556.5 nm using 1552.5 nm control pulses. By appropriately setting the loss and polarization of light within the WC, we were able to generate a 10-GHz train of high-quality 3.5-ps pulses at 1556.5 nm.

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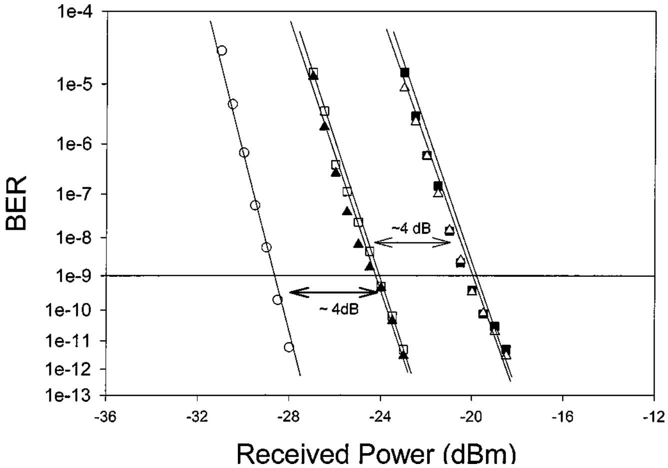

Fig. 4. Above: BER curves for various combinations of interfering channels measured against received power: Laser back-to-back (open circles), Q1:Q1* (closed triangles), Q1+ Q2:Q1* (open triangles), Q1+ B3+ B4:Q1* (open squares), Q1+ Q2+ B3+ B4:Q1* (closed squares).

The individual pulse streams at the two wavelengths were then reflected off one of four coding gratings to generate four separate coded data channels. The 1.25-Gb/s 1552.5-nm channels were encoded with either one of two "orthogonal" 255-chip 320-Gchip/s quadrature code sequences (Q1, Q2). The 10-GHz channels at 1556.5 nm were encoded with either one of two 63-chip 160-Gchip/s bipolar code sequences (B3, B4) corresponding to two "orthogonal" gold code-sequences. The characteristics of these particular gratings have been reported previously [1].

All four channels were combined into a single fiber and the resulting signal fed onto an appropriate decode grating matched to the particular channel that we wished to decode. (These gratings are correspondingly denoted by Q1*, Q2*, B3* or B4*). Note that the inherent wavelength selectivity of the grating can be used both to provide wavelength channel selection, as well as the decoding function for "inband" signals, eliminating the requirement for additional wavelength channel filtering elements [4].

After convolving with the input pulse spectrum, both 63-chip and 255-chip OCDMA channels exhibit a full bandwidth of ∼ 2 nm. The wavelength spacing of 4 nm used in this experiment was chosen to ensure that the system suffered no significant WDM crosstalk. It is worth noting that although the current experimental system has a relatively low spectral efficiency, the use of such long code sequences should support a far larger number of users per wavelength channel than demonstrated herein, (theoretically of the order of several tens of users when used in conjunction with nonlinear thresholding techniques [5]). It has also been shown that the use of nonlinear optical filtering techniques permits denser wavelength spacings in WDM/OCDMA systems, indeed spectral efficiencies as high as 1.6 Bit/s/Hz have recently been experimentally demonstrated [6].

In Fig. 4, we plot BER measurements made on the individual 255-chip Q1 channel in the presence of various combinations of interfering channels. A number of features are apparent. Firstly, there is no power penalty observed when additional channels at a second wavelength (1556.5 nm) are added, even when these channels operate with different coding schemes and repetition rates. The ∼4-dB power penalty observed when comparing the BER cases corresponding to the channel combinations Q1+ Q2+ B3+ B4:Q1* with Q1+ B3+ B4:Q1* results primarily from the increased average power due to the addition of the second "inband" channel (Q2), although a contribution from coherent interference noise between the code sequences also arises. However, we have already experimentally shown that by adopting nonlinear filtering after the matched decode grating, we can significantly reduce such a power penalty [7]. Note that the individual pattern recognition signatures each have a total length of 1.6 ns. At a data rate of 1.25 Gb/s, the tails of adjacent recognition signatures overlap. This provides an additional element of interference noise which contributes the majority of the ∼4-dB power penalty measured when comparing Q1:Q1* relative to the back-to-back measurement.

IV. CONCLUSION

We have experimentally demonstrated that the SSFBG's coding/decoding approach can be extended to far longer code sequences and chip rates than hitherto thought possible. We have also demonstrated the viability of quaternary phase coding and demonstrated an elementary four-channel, multitransmission format WDM/OCDMA system. The SSFBG approach is attractive in that it is far more flexible (and low cost) from a fabrication perspective than other DS-coding techniques, and has the resolution needed to allow a far broader range of codes and potential coding schemes. It is to be appreciated that although the encoder and decoder SSFBGs used in these experiment worked with fixed codes, the use of established grating tuning approaches should ultimately allow the development of code-tunable SSFBGs. We consider that these results further demonstrate that the SSFBG approach provides an extremely powerful and flexible way of performing many of the elementary optical processing functions required within both OCDMA and packet-switched networks.

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