

Spectrally Efficient Six-User Coherent OCDMA System Using Reconfigurable Integrated Ring Resonator Circuits

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Abstract—We demonstrate a spectral phase encoded optical code-division multiple-access system using programmable ring-resonator-based integrated coders. A six-user polarization multiplexed system operates at data rates of 5 Gb/s within an 80-GHz transparent optical window with a bit-error rate of 5×10^{-11} or better and a high spectral efficiency of 0.375 b/s/Hz.

Index Terms—Fiber-optics communications, integrated optics, optical code-division multiple-access (OCDMA).

I. INTRODUCTION

OPTICAL code-division multiple-access (OCDMA) is a rapidly advancing area [1] with researchers pursuing higher bit rates and capacity, multiuser interference (MUI) reduction schemes, new coding designs, and investigation of elementary networking functions. Different approaches to implementing OCDMA are based on the working principle (coherent and incoherent), timing coordination for multiuser access (synchronous and asynchronous), and on the coding scheme (time and/or frequency domain and amplitude and/or phase). *Spectral phase encoded* (SPE) OCDMA in particular is based on the ability to manipulate the optical phase of the spectral components of a broadband signal according to a set of codes that define a unique choice of phase shifts [2]

Recent OCDMA demonstrations have mostly had low spectral efficiency (0.2 b/s/Hz or less) and occupy large spectral bandwidths (400 GHz or higher) [3]–[6], except in [7], where a high spectral efficiency system using *temporally phase encoded* OCDM along with wavelength-division multiplexing (WDM) was shown to operate on a 200-GHz ITU grid. Here we present a spectrally efficient, SPE OCDMA system in which the spectral bandwidth is confined to just 80 GHz thus making it compatible with current dense WDM (DWDM) networks (and their components) operating on a 100-GHz ITU grid. This is achieved by the application of integrated ring resonators circuits that provide ultrahigh frequency resolution. Other key advantages of our system include the use of orthogonal codes to suppress MUI and lossless scalability to longer code lengths both of which lead to scalability for the number of simultaneous users.

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We have demonstrated a six-user SPE OCDMA system at data rates of 5 Gb/s with an uncorrected bit-error rate (BER) of 5×10^{-11} or better. Ring-resonator-based programmable integrated devices are employed as spectral phase coders to modify the spectral phase characteristics of a coherent signal with high frequency resolution. The fine resolution (i.e., channel spacing of 10 GHz) provided by these integrated coders allows us to limit the coded signal's spectral bandwidth leading not only to a high (compared to other pure OCDMA system demonstrations) spectral efficiency of 0.375 b/s/Hz, but also ensuring compatibility with conventional DWDM networks [8]. Besides their use as OCDMA coders, these novel circuits have a variety of applications in optical signal processing and wavelength filtering.

II. SPECTRAL PHASE ENCODING

Our coherent spectral phase encoding approach consists of demultiplexing *individual* spectral components of a mode-locked laser (MLL) signal, shifting the phase of each component according to a code, and recombining the shifted components to produce a coded signal. This can be combined with signals from other users, each of which is assigned a unique code. Spectral encoding leaves the amplitudes of frequency component unaltered, shifting only their relative phases, resulting in time-spreading of the input signal pulse. At the receiver, a phase conjugate decoder realigns the phase of the individual frequency components to reconstruct the original pulse, while incorrectly decoded signals remain temporally broadened. The desired correctly decoded signal pulse can be extracted by optical time gating.

The reconfigurable integrated spectral phase coder [9] consists of a common input bus and a common output bus, with fourth-order microring resonators serving as bandpass filters between the two, as shown in Fig. 1. Each passband representing a frequency bin has a 3-dB bandwidth of 8 GHz and selects individual MLL lines and associated sidebands resulting from user data modulation. In the current second-generation device, eight bins spaced on a 10-GHz frequency grid are used. The measured loss of the device is 4 dB. Fig. 1(b) shows two measured intensity transfer functions of these coders. The relative phase shift between two adjacent frequency bins is controlled by a thermo-optic phase heater. This phase shift is programmable and can be continuously varied between 0 and π on a millisecond time-scale. The coder thus selects eight MLL frequency components and individually shifts their relative phases according to the code. In our demonstration, we chose to manipulate the

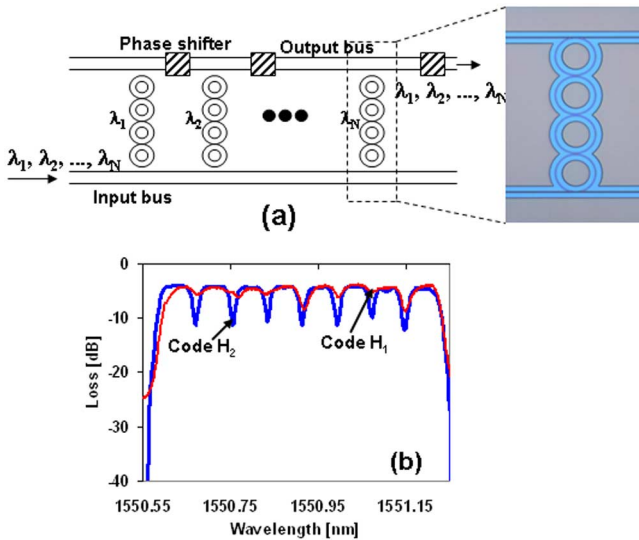


Fig. 1. (a) Integrated spectral phase coder based on ring resonator filters. Micrograph shows the ring resonator heaters. (b) Spectral intensity response.

relative phase of individual MLL components using orthogonal Hadamard codes in order to suppress MUI [10].

The temporal response of an encoder to an MLL pulse train with a repetition frequency of 10 GHz is shown for the conventional Hadamard-8 codes (H_1 to H_8) in Fig. 2(b) using a 30-GHz photodetector. The experimental waveforms match closely with the simulated results [Fig. 2(a)], illustrating successful encoding operation. Once encoded, the signal can be decoded to recover the original pulse in the correct time-slot by applying a matched conjugate spectral phase code. This is illustrated in Fig. 2(c) when the decoder is matched to decode code H_4 . As expected, incorrect decoding leaves the energy of the pulse distributed away from the central position at which the correctly decoded signal is at its peak (shown by the thick arrow).

III. EXPERIMENTAL SETUP AND RESULTS

Next, we present the six-user SPE OCDMA system using programmable ring-resonator-based integrated coders. The experimental setup is shown in Fig. 3. The output of a 10-GHz MLL is split by a 1×4 splitter. Three of the outputs are independently modulated by 5-Gb/s data streams consisting of $2^{31} - 1$ pseudo-random bit sequences. The ON-OFF keyed modulation rate must be chosen so that the modulation-induced spectral broadening of each of the MLL lines is confined to within the bandwidth of the frequency bin (8 GHz) [10]. This leads to a modulation format consisting of two pulses per bit. The modulated signals are then encoded in three separate programmable eight-channel spectral phase encoders, each of which is assigned a unique code from the Hadamard-8 code set. In this experiment, the codes used are H_2 , H_3 , and H_4 . The output after each encoder is split using a 1×2 splitter for polarization multiplexing in order to emulate six simultaneous users. The output of each user, first equalized in power, is connected to a fiber delay line to provide the appropriate synchronization with other users, all of which are then passively combined. A polarization beam splitter is used

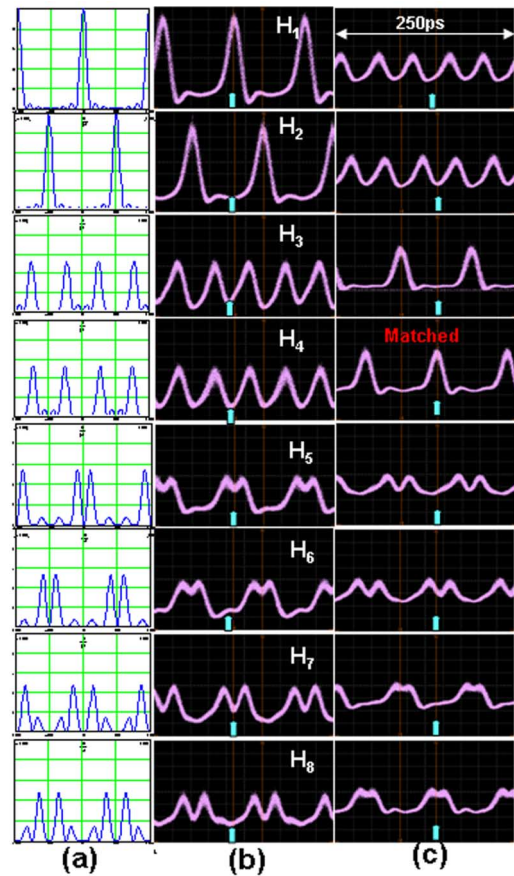


Fig. 2. Temporal response to MLL pulse train after eight-channel encoder using Hadamard codes (a) simulation, (b) experiment; (c) after decoder matched to code H_4 .

to combine users in orthogonal polarizations. All six users occupy the same 80-GHz spectral bandwidth (eight frequency bins \times 10 GHz), thus providing compatibility with existing DWDM systems.

At the receiver, polarization demultiplexing is followed by a reconfigurable eight-channel decoder, which is programmed to correctly decode any of the six users by selecting the corresponding phase code. Optical time-gating using a terahertz optical asymmetric demultiplexer [11] provides MUI rejection by extracting the desired decoded channel from the remaining incorrectly decoded signals. This is followed by another time gate implemented with a Mach-Zehnder modulator driven with a 5-GHz clock to select one pulse out of the two that represent a data bit in order to reduce intersymbol interference (ISI). The second gate is critical to obtaining a good BER performance.

The BER performance is shown as a function of the received power (per user) in Fig. 4 for the cases of two, four, and six simultaneous polarization multiplexed OCDMA users. For a given number of users, similar performance is measured for all users. To maintain clarity, however, BER curves are shown only for code H_4 decoded. An uncorrected BER of 5×10^{-11} or better is obtained in all cases, illustrating successful suppression of MUI and ISI. With the system operating with six simultaneous OCDMA users (each of which is operating at 5 Gb/s) and the occupied bandwidth confined to 80 GHz, the resulting

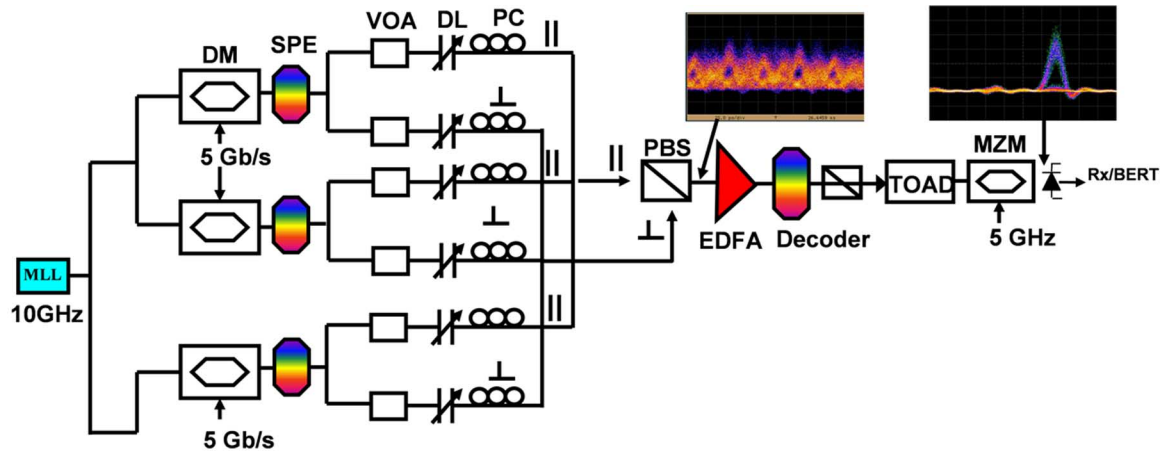


Fig. 3. Experimental setup: DM: Data modulator. VOA: Variable optical attenuator. DL: Delay line. PC: Polarization controller. PBS: Polarization beam splitter. EDFA: Erbium-doped fiber amplifier. MZM: Mach-Zehnder modulator. Rx/BERT: Receiver and BER detector set.

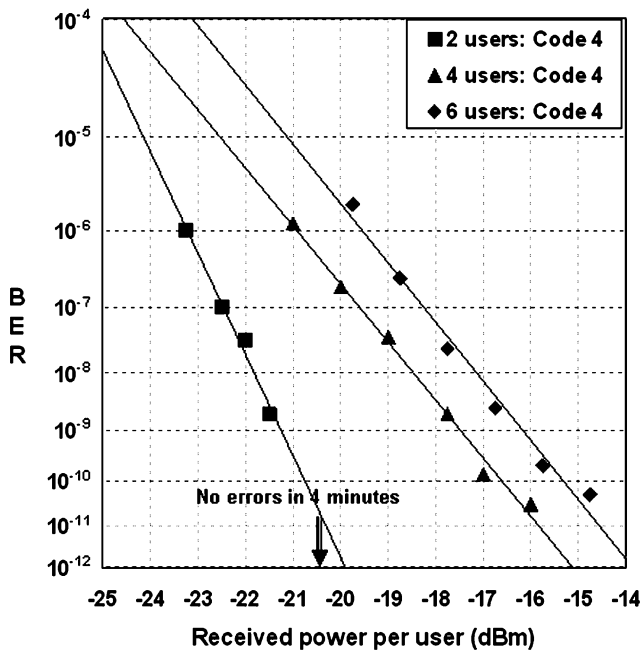


Fig. 4. BER performance for two, four, and six simultaneous OCDMA users.

spectral efficiency is 0.375 b/s/Hz. Future work is focused at increasing the spectral efficiency further, with a goal of 100% by increasing the number of users and increasing the data rate per user.

IV. CONCLUSION

We have demonstrated a spectrally efficient six-user SPE OCDMA system operating with bit rates of 5 Gb/s at a BER performance of 5×10^{-11} or better. The ultrafine frequency resolution of the ring-resonator-based integrated coders gives us the unique flexibility to encode the phase of *individual* tightly spaced frequency components of an MLL and limits the

spectral bandwidth occupied by the coded signal, thus allowing for high spectral efficiency and compatibility with existing DWDM systems.

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