# Fully Programmable Ring-Resonator-Based Integrated Photonic Circuit for Phase Coherent Applications

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***Abstract*—A novel ring-resonator-based integrated photonic chip with ultrafine frequency resolution, providing programmable, stable, and accurate optical-phase control is demonstrated. The ability to manipulate the optical phase of the individual frequency components of a signal is a powerful tool for optical communications, signal processing, and RF photonics applications. As a demonstration of the power of these components, we report their use as programmable spectral-phase encoders (SPEs) and decoders for wavelength-division-multiplexing (WDM)-compatible optical code-division multiple access (OCDMA). Most important for the application here, the high resolution of these ring-resonator circuits makes possible the independent control of the optical phase of the individual tightly spaced frequency lines of a mode-locked laser (MLL). This unique approach allows us to limit the coded signal's spectral bandwidth, thereby allowing for high spectral efficiency (compared to other OCDMA systems) and compatibility with existing WDM systems with a rapidly reconfigurable set of codes. A four-user OCDMA system using polarization multiplexing is shown to operate at data rates of 2.5 Gb/s within a 40-GHz transparent optical window with a bit error rate (BER) better than $10^{-9}$ and a spectral efficiency of 25%.**

***Index Terms*—Fiber-optics communications, integrated optics, optical code-division multiple access (OCDMA), pulse shapers, ring resonators.**

## I. INTRODUCTION

OPTICAL-PHASE control has attracted considerable interest lately and is opening exciting new possibilities in optical communications, signal processing, and RF photonics applications. This paper describes a novel reconfigurable device, based on ring-resonator technology that has the ability to select frequencies and shift their relative phases, enabling us to precisely tailor the spectral-phase characteristics of a broadband coherent optical signal with ultrahigh-frequency resolution. The success of this demonstration depends critically on the accuracy, stability, and tunability of the constituent filters and phase shifters.

Microring resonators are highly suitable for the realization of narrowband selective bandpass filters and immense progress has been made in the design and fabrication of high-performance optical filters based on ring resonators [1]–[10]. Apart from channel filtering, microring resonators find various applications in optical add/drop multiplexers [11]–[15], dispersion compensation [16], [17], signal processing [18], switching [19], [20], and are particularly attractive due to their compactness and their ability to provide wavelength selectivity, sharp filter response, and high extinction ratio. In addition, microring resonators are easily cascadable, thus allowing the realization of various filter responses through multiple coupled ring resonators, and can be integrated with other optical components such as variable optical attenuators (VOA) to enable complex optical processing.

We demonstrate for the first time to our knowledge the use of such rapidly reconfigurable ring-resonator-based optical circuits to perform all-optical encoding/decoding. Further, we demonstrate their application as spectral-phase encoders (SPE) and decoders in an optical-code-division-multiple-access (OCDMA) system. The encoder/decoder is a key element in an OCDMA system, where different users' signals are overlapped in time and frequency, and hence, multiple users are distinguished on the basis of the codes assigned to them [21]–[46]. In previous demonstrations, the encoder/decoder technologies have included spatial light modulators (SLMs) [30], [31], [43], delay lines [32]–[34], hyperfine channelizers [28], [47], [48], [51], planar lightwave circuits (PLCs) [35], fiber Bragg gratings (FBGs) [36]–[39], superstructured FBGs (SSFBGs) [40]–[42],

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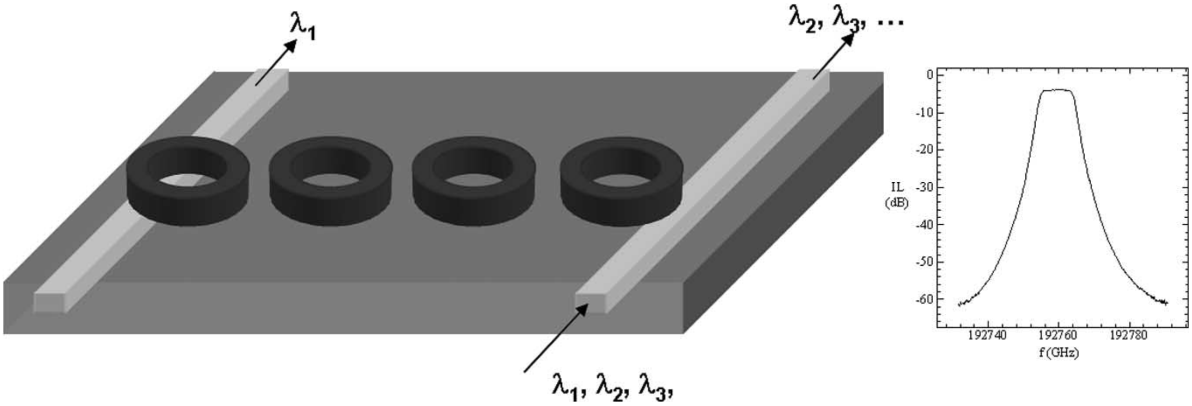

Fig. 1. Fourth-order microring-resonator filter comprised of four coupled rings. The input and output bus waveguides are vertically coupled to the rings while the rings are laterally coupled to their neighbors. Inset: Measured response at the drop port for an isolated fourth-order microring-resonator filter having a 3-dB bandwidth of 8 GHz.

and arrayed waveguides (AWGs) [44]. These approaches suffer from one or more limitations such as high cost, low spectral efficiency, large size, and/or low frequency resolution. In contrast, our ring-resonator-based encoder/decoder is ultracompact and offers several key advantages such as ultrahigh-frequency resolution with programmable, stable, and accurate phase control, all of which combine to make it viable for realistic applications.

As with CDMA wireless networks, OCDMA offers the potential of increased network functionality and flexibility by enabling network functions such as addressing and routing through all-optical code translation, which is entirely passive, unlike wavelength translation in a wavelength-division-multiplexing (WDM) network, which is active. Furthermore, OCDMA offers the potential for low probability of interception and detection. Different approaches to implementing OCDMA are based on the working principle (coherent and incoherent) and on the coding scheme (time and/or frequency domain and amplitude and/or phase), with each scheme having its own set of advantages and disadvantages. Furthermore, depending on the timing coordination for multiuser access it can be classified as synchronous or asynchronous. As explained below, both have advantages and disadvantages, and the choice between the two should be based on the application and the system requirements. A synchronous system requires very strict timing coordination among users, whereas an asynchronous system requires very little if not any coordination among users. However, a synchronous system has some key advantages such as, in principle, there is no multiuser interference (MUI) and the system is noise limited, the optimal receiver is the single-user matched filter (SU-MF), and hence, each user can be detected independently [58], high spectral efficiency is achievable (for codes of length $N$, up to $N$ users are possible), and finally, the measured bit error ratio (BER) is stable and weakly dependent on the system load. In contrast, in an asynchronous system, MUI is always present and the system is interference limited, SU-MF is suboptimal and optimal detection requires access to all outputs of the matched filters [58], spectral efficiency is lower, and most importantly, the BERs are time varying [57] and strongly dependent on the system load. Hence, in a synchronous system, a global time reference among all users is the price to pay for the advantages offered, while in an asynchronous system, the advantage of not requiring a global time reference comes at a price.

OCDMA is a rapidly advancing area with progress made in recent years on devices for optical en/decoding [29], [41], [44]–[46], performance improvement through MUI reduction [30], [31], [34], [35], [42], [43], coding designs [31], [33], [35], and even elementary networking-function demonstrations [49], [50].

Here we demonstrate the use of ring-resonator-based circuits in an OCDMA system based on the spectral-phase encoding of phase-locked lines of a mode-locked laser (MLL). Our coherent spectral-phase-encoding [22] approach consists of demultiplexing the individual MLL lines that make up a signal, shifting the phase of each line according to a code, and recombining the shifted lines to produce the coded signal. Basing the OCDMA code on the phase control of individual spectral lines limits the spectral bandwidth occupied by the coded signal, allowing high spectral efficiency and compatibility with existing transparent WDM systems [47], [48]. To do so, however, requires the ability to access each of the closely spaced (10 GHz) spectral lines, to guarantee that optical paths within a particular OCDMA encoder or decoder remain stable to a fraction of a wavelength, and to create the desired phase changes accurately, stably, and reproducibly. Our ultracompact commercially viable ring-resonator device is ideally suited to this application.

## II. PRINCIPLE OF OPERATION

In this section, we describe the construction and characterization of ring-resonator-based photonic integrated circuits and how they can be used to perform the coding/decoding functions.

### A. *Device Technology*

A fourth-order microring-resonator filter, depicted in Fig. 1, is the basic building block for the OCDMA coder/decoder. It comprises four microrings that are vertically coupled to a pair of input/output bus waveguides. Vertical coupling allows for more precise control of the coupling strength than lateral coupling, since the vertical separation of the guides depends on the thickness of the intervening layer and is not determined by mask error, photolithography, or etching, all of which

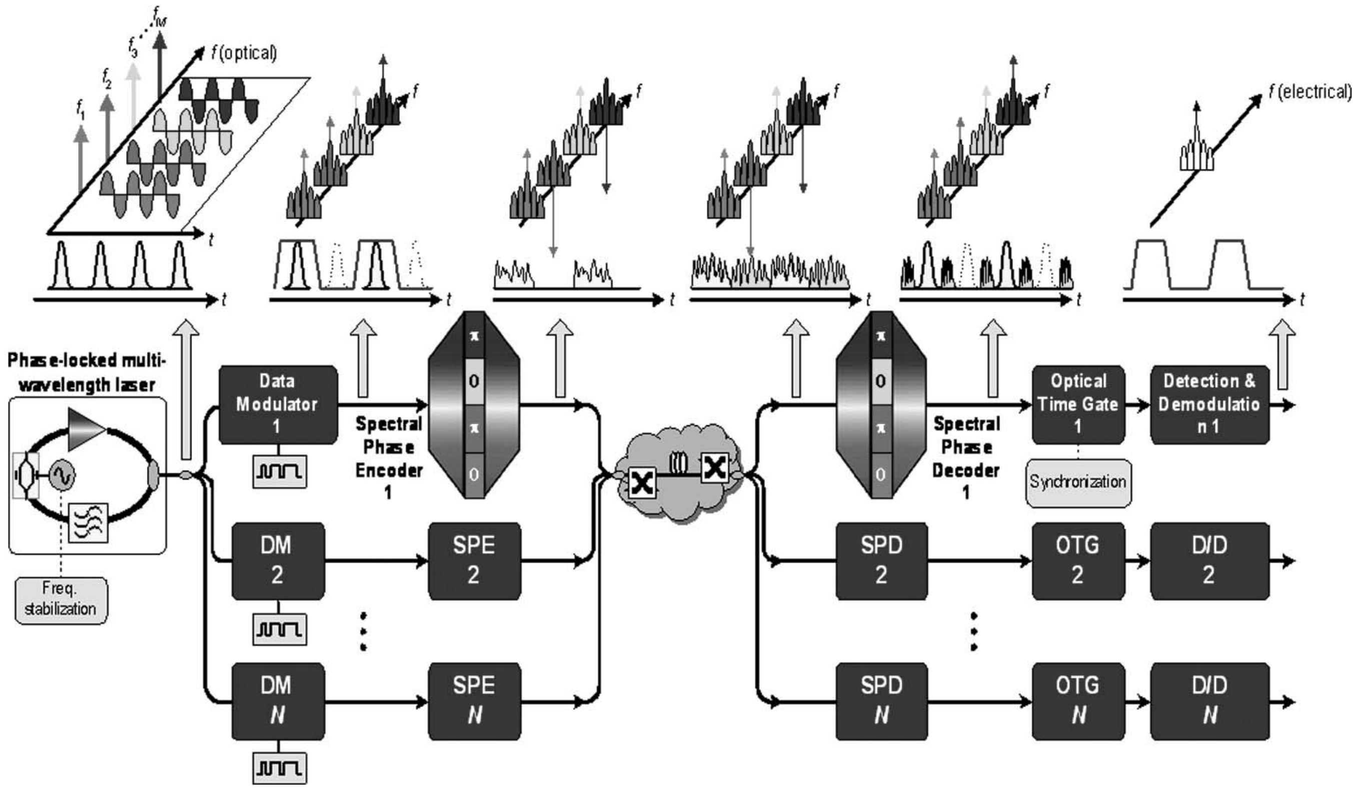

Fig. 2. Conceptual diagram of spectral-phase coding.

are more difficult to control with the required precision and reproducibility. In high-order microring-resonator filters that are designed to have a maximally flat passband, the coupling between the bus waveguide and the ring needs to be strong, whereas the coupling between adjacent rings is designed to be weak. In order to achieve strong coupling between ring and bus in a lateral configuration, the gap between the two would be subresolution, and therefore, subject to large random deviations. Vertical coupling allows the ring and bus to come into close proximity without the need to etch an ultranarrow coupling gap. Instead the coupling is determined by well-controlled material deposition. The rings support resonant traveling wave modes and the resonant condition is determined by the circumference and effective index of the rings. At resonant wavelengths, optical power can be transferred completely from one bus waveguide to the other via the rings, as shown by $\lambda 1$ in Fig. 1, while off-resonant $\lambda 2, \lambda 3, \ldots$ wavelengths bypass the rings. The shape and bandwidth of the filter response is determined by the number of rings in the filter, the mutual coupling strength among the rings, and between the outer rings and the bus waveguides. By appropriately coupling multiple rings, the frequency response of the filters can be tailored to a desired response. As the number of coupled rings increase, the order of the filter increases, leading to a box-like filter response. These higher order filters, while dispersionless at the center of the passband, can have larger dispersion at the edges. Ongoing work includes the optimization of the filter design to minimize this dispersion.

For strong optical confinement with small bending radii, microrings require a high index contrast. Hydex, a low-loss high-index-contrast glass-based material system is used to fabricate the ring resonators. The waveguide-core refractive index is 1.70, while the cladding is 1.45, giving a refractive-index-contrast ratio of 17% with respect to the cladding. A larger index-contrast ratio enables the use of a smaller bending radius, thus allowing for a higher free spectral range (FSR). The ring and bus waveguide cores have cross sections of $1.5\ \mu\text{m} \times 1.5\ \mu\text{m}$. The rings have radii of 47 $\mu$m, resulting in an FSR of 575 GHz. Microheaters (seen in Fig. 3) are placed over all the rings for fine tuning. The propagation loss is less than 0.2 dB/cm over the C-band, and close to 0.1 dB/cm at 1550 nm. The inset in Fig. 1 shows the response at the drop port of a fourth-order filter having a 3-dB bandwidth of 8 GHz.

### *B. Spectral-Phase Coding*

The basic concepts of spectral-phase coding are illustrated in Fig. 2. The output of an MLL is a train of short pulses in the time domain and a comb of phase-locked frequencies spaced at the pulse repetition rate in the frequency domain. Spectral-phase encoding and decoding comprises three operations: First, individual frequencies of the MLL are demultiplexed; then, each spectral line is phase shifted depending on the code; and finally, these shifted frequency components are recombined to produce the coded signal; this can also be viewed as pulse shaping [56]. Encoding results in time-spreading of the input signal but leaves the set of frequencies unaltered, shifting only their relative phases. At the receiver, only a phase-conjugate decoder can realign the phase of the shifted frequency components, thus recovering the original pulse, while incorrectly decoded signals

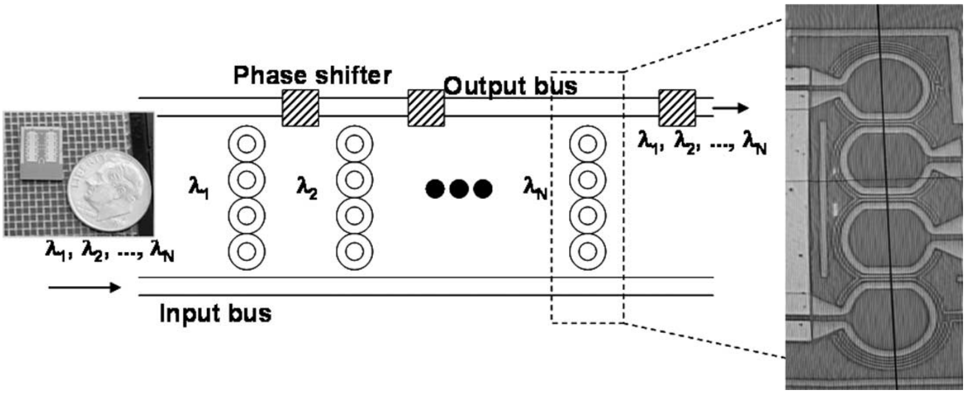

Fig. 3. Schematic of the optical circuit, incorporating fourth-order microring-resonator filters. Micrograph shows the ring-resonator heaters.

remain temporally broad. The desired correctly decoded signal can be extracted by appropriate optical time gating.

For spectral-phase coding, the coder/decoder circuit consists of a common input bus and a common output bus, with fourth-order microring resonators serving as wavelength-selective cross connects between the two as shown in Fig. 3. A fourth-order filter cell occupies an on-chip area of $100 \times 400$ $\mu$m, allowing a large number of filter cells on a chip (64 filter cells on a $17 \times 17$ mm chip). Each filter is independently tunable in wavelength and each passband represents a frequency bin. In this first implementation of the narrowband filters for each frequency bin, all rings in each fourth-order filter were made identical. An independent heater is placed over each of the four rings in order to give the maximum amount of flexibility in this first design run. Generally, the nominally identical rings come out very close to each other in resonant wavelength but the heaters can be differentially adjusted to fine tune the optical line shape. Generally, this differential tuning is small and fixed, and thereafter, the entire filter bin can be tuned as a single unit. The different filter bins also all have nominally identical ring designs. The operating wavelengths are set by thermally tuning each bin by the desired amount. There are resistive thermal devices (RTD) placed on each filter bin, and these mitigate the effects of thermal crosstalk. If by thermally tuning one bin, the temperature of an adjacent bin changes, the RTDs provide an error signal to the control electronics to null the temperature change. In this paper, we present results obtained with devices having four frequency bins. The bins are spaced by 10 GHz with each passband having a 3-dB bandwidth of 8 GHz. The relative phase shift between two adjacent frequency bins is controlled by a separate thermooptic phase heater, shown hatched in Fig. 3, and can be continuously varied between 0 and $\pi$. Hence, the microrings provide the wavelength selectivity, and the thermooptic heater is used to control the relative phase of individual wavelengths. The phase heaters are sufficiently isolated from the heaters for the rings. The center wavelength can be tuned via a thermoelectric cooler (TEC); tuning the wavelength does not affect the phase coding. Due to the symmetry of this configuration, the optical path lengths from the input to the output are the same for all wavelengths, and hence, the original phase relationships are maintained for all wavelengths when the phase heaters are not activated. The three necessary functions, frequency demultiplexing, phase shifting, and recombining the phase-shifted frequencies, are all accomplished in this single integrated device. One issue is the thermal crosstalk between neighboring components. RTDs are used with each critical component to sense temperature changes and automatically adjust the supplied power accordingly to mitigate thermal crosstalk. While in our current application the thermal crosstalk has been calibrated out, future applications look at reducing the impact of thermal crosstalk through improvements in device technology. Also, microring filters with such a narrowband wavelength response tend to be polarization dependent. Polarization diversity can be implemented to make the devices polarization insensitive [54].

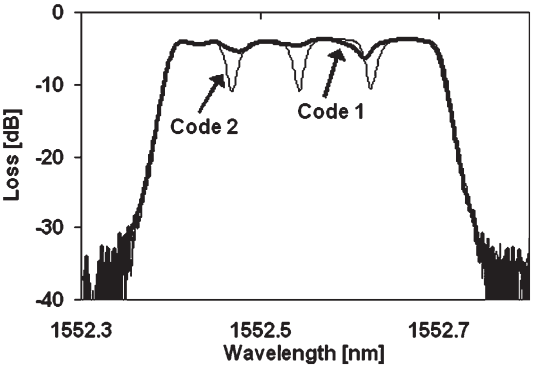

Fig. 4. Spectral-intensity response for four-frequency bin devices.

### C. Spectral Amplitude and Phase Characterization

For the OCDMA demonstration, we apply either a 0 or $\pi$ phase shift and have chosen to use Hadamard codes. In our approach, the codes are optically orthogonal, and hence, minimize the MUI at the time position when the desired decoded signal is maximum. Each code is defined by a unique choice of phase shifts. There are as many orthogonal Hadamard codes as there are frequency bins. The codes are represented in terms of the phase, where 0 indicates a zero phase shift, and 1 indicates a $\pi$ phase shift. Fig. 4 shows the spectral intensity response for the encoder set to codes 1 and 2, as measured with a broadband source for a device with four frequency bins. The output is flat-topped with a sharp filter response; sharp dips are seen in the

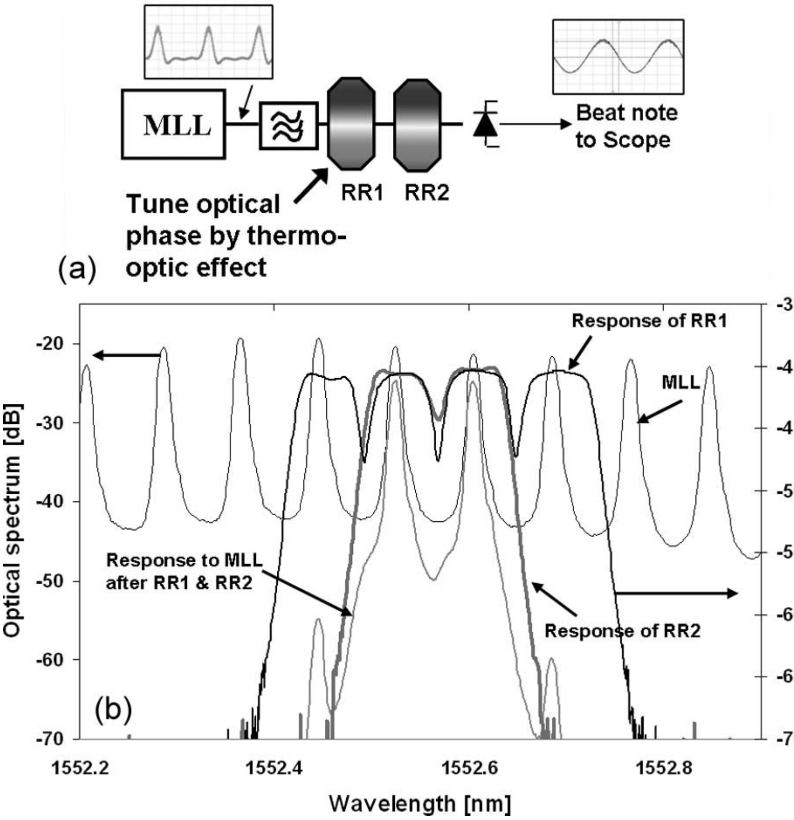

Fig. 5. Spectral phase characterization. (a) Schematic of setup. (b) Illustration of selection and beating of two mode-locked laser lines. The two curves MLL and Response to MLL after RR1 and RR2 are plotted on the primary $Y$-axis, whereas Response of RR1 and Response of RR2 are plotted on the secondary $Y$-axis.

spectrum when the relative phase difference between adjacent frequency bins is $\pi$. The 3-dB bandwidth is 8 GHz with a spacing of 10 GHz between the frequency bins. The fiber-to-fiber loss of the devices is 4 dB.

Our pulse source is an actively mode-locked fiber laser set to a pulse repetition rate $(f_{\mathrm{r}})$ of 10 GHz. The laser, centered at 1552.52 nm (193.1 THz), is matched to the center of the encoder and produces a train of transform-limited 2-ps pulses. The output spectrum is a comb of phase-locked frequencies equally spaced at 10 GHz. The SPE selects four of these frequency lines and individually shifts their phases by either 0 or $\pi$ depending on the choice of code.

Important to the encoding/decoding process is the characterization of the phase. We have developed a method to measure the phase shift imparted as the phase heaters are tuned (a technique based on a similar concept was developed independently by another group [55]). This is accomplished by two ring-resonator devices in cascade after the MLL. The first device selects four frequency bins, while the second device passes only two of the four bins, as illustrated in Fig. 5. Since the frequency bins are wavelength tunable, the second device can select any two of the four bins from the first in order to characterize the response of the phase heater between the two adjacent bins on the first device. The phase heaters are not activated on the second device. This configuration selects two frequency lines of the MLL phase-locked comb spaced at the pulse repetition rate (10 GHz). The beating of these two frequencies leads to a sinusoidal waveform at a frequency of 10 GHz with a phase related to the phase shift obtained from successively tuning the phase heater. This is illustrated in Fig. 6. Fig. 6(a) shows the oscilloscope traces of the 10-GHz sinusoidal waveform as one of the phase heaters is tuned. The reference is obtained for a phase-heater setting of zero. As the phase-heater setting is increased, the shift in the phase of the sinusoidal waveform with respect to the reference waveform is clearly seen and can be accurately measured. Fig. 6(b) shows the relative phase shift (in units of $\pi$) obtained for the three phase heaters as a function of the corresponding phase-heater settings. The phase shift is linear, stable, and reproducible from heater to heater to within $\pi/10$. After calibration, the error in the phase control of individual heaters is on the order of 2%. The use of two cascaded devices allows us to determine not only the phase shift obtained with tuning the phase heaters but also takes into account any differential phase shifts already present in the device, for instance, due to residual optical-path-length differences. For this, the phase of the sinusoidal waveform obtained for the first phase heater for a heater setting of zero is used as a reference for the other two phase heaters in order to obtain the differential phases between the three phase heaters when not activated. We thus have the valuable ability to not only manipulate the optical phase of the individual frequency components of a signal, but also to simply measure it electrically.

### *D. Temporal Response*

With the phase accurately characterized, we next look at the temporal response of the encoder. Spectral-phase encoding of the MLL frequency lines results in time-spreading of the

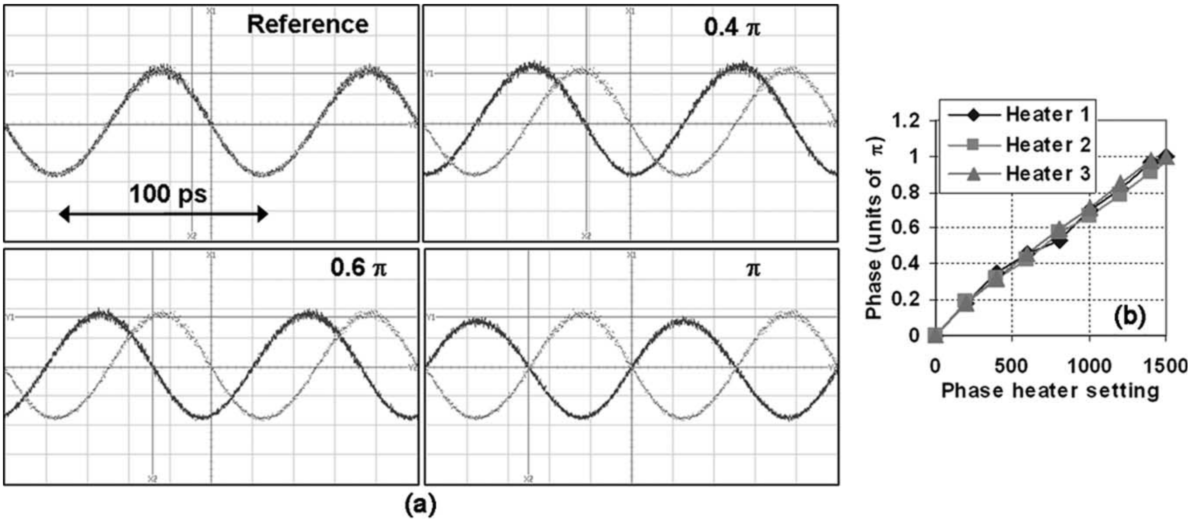

Fig. 6. Phase characterization results.

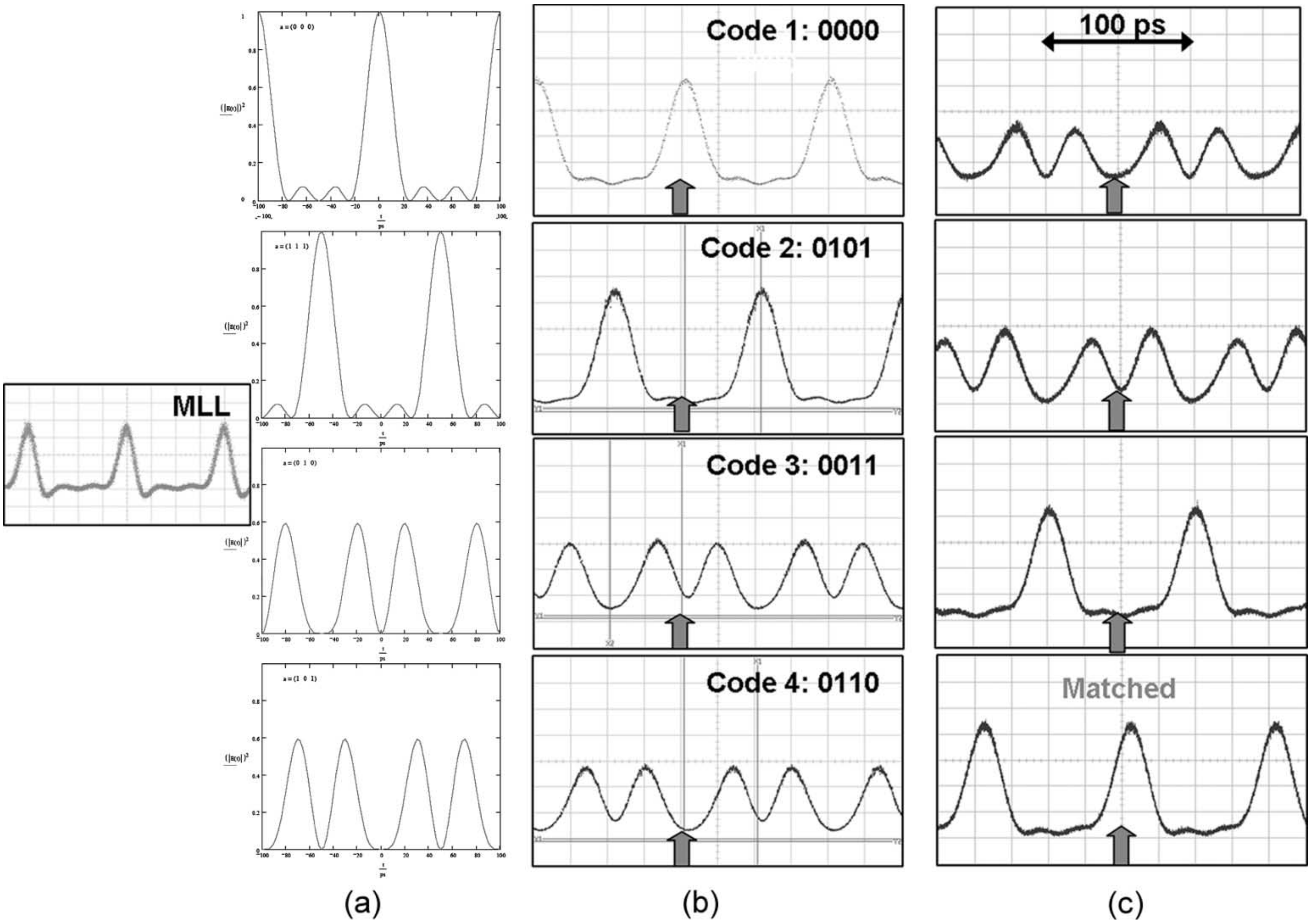

Fig. 7. Temporal response for an MLL pulse train after the four-frequency bin encoder using Hadamard codes. (a) Simulation. (b) Experiment. (c) After the decoder matched to code 4.

input pulses. The resulting temporal pattern corresponding to the four orthogonal codes is shown in Fig. 7(b). Encoding (except for code 1, where the phases are unchanged) temporally spreads the pulse energy away from the central position of the original uncoded pulse (shown by the thick arrow). Also shown for comparison is the simulated temporal response [Fig. 7(a)]. The experimental results match closely with the simulated results. Once encoded, the signal can be decoded to recover the original pulse in the correct time slot by applying a conjugate spectral-phase code. The decoded signal recovers

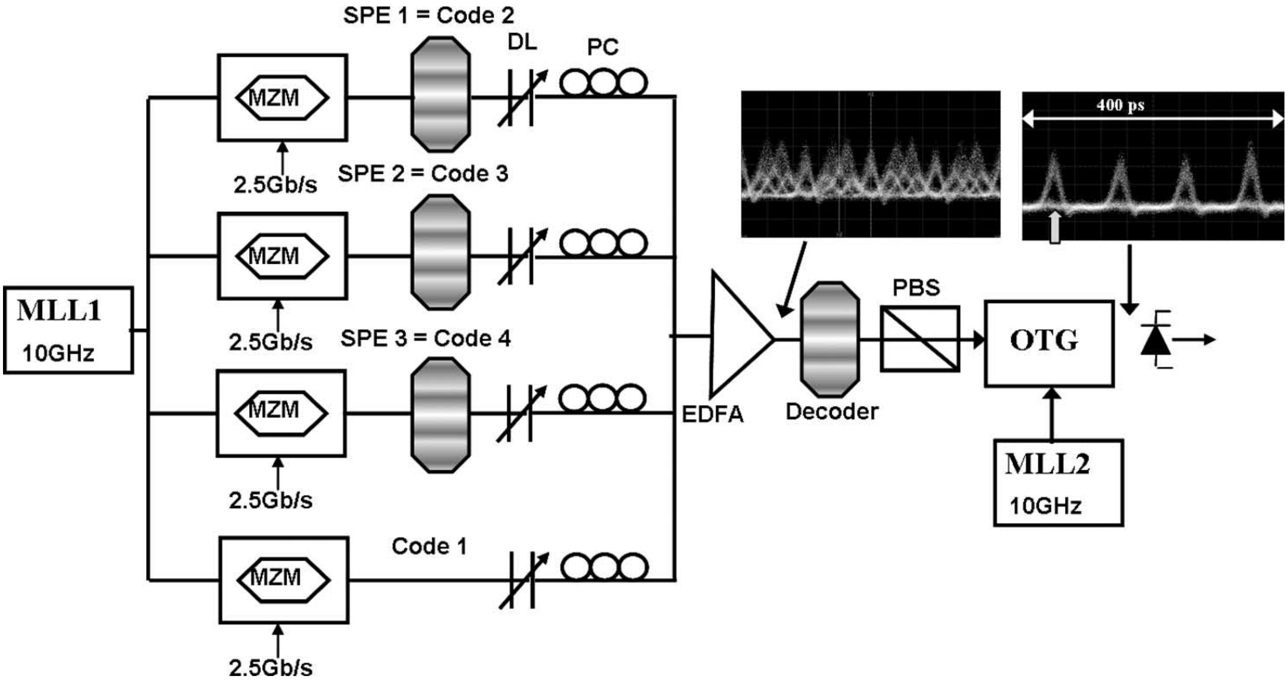

Fig. 8. Experimental setup—MLL: mode-locked laser. MZM: Mach–Zehnder modulator. SPE: spectral-phase encoder. DL: delay line. PC: polarization controller. TOAD: terahertz optical asymmetric demultiplexer. PBS: polarization beam splitter. Rx/BERT: receiver and bit-error-rate detector set.

the original pulse only when the encoder and decoder are matched. This is illustrated in Fig. 7(c), when the decoder is matched to code 4. It is seen that for code 4 the original pulse is recovered, whereas for all the other three codes, decoded incorrectly, the energy of the pulse remains distributed away from the central position of the correctly decoded signal. Two coders in series produce another code, which is code 1 if both coders are identical or some other Hadamard code if they are not.

## III. APPLICATION TO OCDMA: EXPERIMENTAL SETUP AND RESULTS

In this section, we present an application of the ring-resonator-based optical circuit for spectral-phase encoding and decoding in an OCDMA system. The four-user synchronous OCDMA experimental setup is shown in Fig. 8. The output of the MLL with $f_r = 10$ GHz is split into four separate paths and each is independently modulated by 2.5-Gb/s data streams consisting of $2^{31} - 1$ pseudorandom bit sequences (PRBS) to generate four OCDMA users. The ON–OFF keyed (OOK) 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). Here we modulate at a data rate of 2.5 Gb/s (it is also possible to modulate at 5 Gb/s) leading to 4 pulses/bit. Each user is assigned a unique code from the Hadamard-4 code set. Due to limited ring-resonator devices available at this time, one user is encoded with a programmable four-frequency-bin ring-resonator SPE (code 2) and two users with static bulk optics Hyperfine SPEs [51], used in our earlier work [28] (codes 3 and 4). The fourth user corresponds to code 1 (where the phases are unchanged). The output of each user, equalized in power, is connected to a fiber delay line for synchronization and then passively combined. The four users are overlapped in both time and frequency. The total occupied spectral bandwidth by the four users is only 40 GHz (four frequency bins × 10 GHz), making this system compatible with existing WDM systems. Also shown in Fig. 8 is the eye diagram after the four users are combined showing all four encoded users. Polarization multiplexing (codes 1 and 2 are orthogonally polarized to codes 3 and 4) is used to further increase the spectral efficiency.

At the receiver, a four-frequency-bin ring-resonator-based decoder, which can be programmed to decode correctly any of the four users by selecting the corresponding phase code, is followed by a polarization beam splitter (PBS). Optical time-gating using a terahertz optical asymmetric demultiplexer (TOAD) [52] serves to provide MUI rejection by extracting the desired decoded channel from the remaining incorrectly decoded signals. A second MLL synchronized to the first provides the clock signal at 1554.13 nm. The TOAD set for a 25-ps switching window operates at an average power of 0.1 mW and provides a suppression of 15 dB. The open-eye diagram after the TOAD shows a single desired user isolated from other interfering users. A commercial OC-48 receiver detects the recovered signal and BER is measured on the regenerated data.

The BER performance is shown in Fig. 9 for a single user and for two and four simultaneous users. With two users, the users, assigned codes 3 and 4 were copolarized. For the four-user case, a similar performance is measured for all four users, but to maintain clarity, BER curves are shown only for codes 2 and 4 decoded. Note that a single programmable decoder

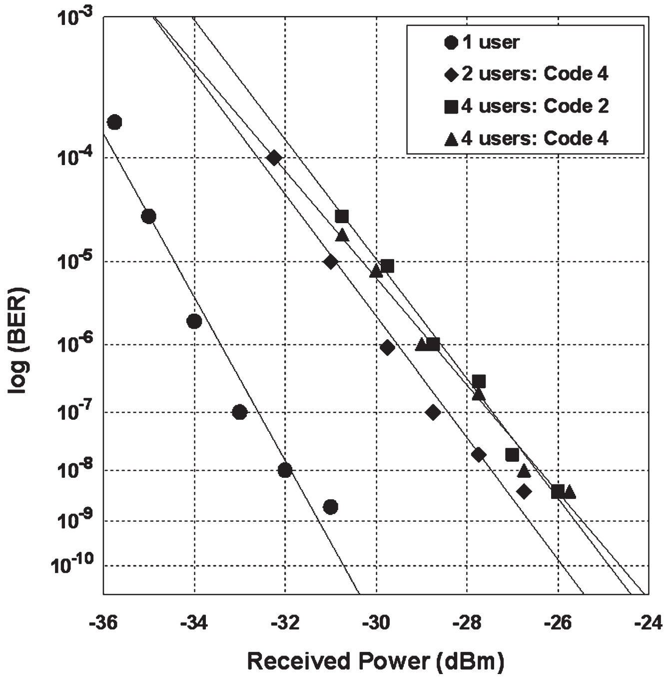

Fig. 9. BER performance with four-frequency bin devices for a single user (●), two copolarized users (◆), and four users measured for codes 2 (■) and 4 (▲).

allows the correct decoding of any of the four users with high fidelity. In all cases, BER $< 10^{-9}$ is obtained. Moreover, the results presented here also establish the compatibility between spectral-phase encoding/decoding devices based on different technologies, allowing for the possibility of employing different technologies at the transmitter and the receiver for the spectral-phase encoding and decoding of optical signals.

The power penalty observed is due to the limited extinction ratio of the optical time gate and coherent crosstalk. An efficient way of compensating for time-gating nonidealities and coherent crosstalk is to limit the number of simultaneously used codes and to choose an optimum subset of codes [53]. The integration and scalability possible in ring-resonator-based integrated photonic circuits allows coders with larger number of frequency bins to be fabricated. In fact, we have designed and fabricated devices with eight frequency bins spaced at 10 GHz and expect to design devices with 16 to 32 frequency bins, which offers the potential for 16 to 32 simultaneous users. In principle, when using orthogonal codes, the number of users can be as high as the number of frequency bins.

## IV. CONCLUSION

We have demonstrated a novel integrated low-loss programmable ring-resonator-based optical circuit with ultrafine frequency resolution and precise optical-phase control for the spectral-phase encoding of picosecond pulses. The ultrafine frequency resolution gives us the ability to demultiplex closely spaced channels and offers the unique flexibility to independently phase encode/decode the individual frequency components of an MLL. A simple technique that provides an accurate measurement of the encoded phase is also presented.

Among the many advantages of our commercially viable ring-resonator-based encoder/decoder, the following are especially notable:

1) programmable and accurate optical-phase control with a reconfiguration time of milliseconds;
2) high level of integration;
3) high spectral resolution equal to the frequency spacing of the input phase-locked comb of an MLL;
4) programmability in both phase and wavelength, allowing the precise tailoring of the spectral-phase characteristics of a broadband coherent optical signal.

All-optical encoders and decoders find many useful applications and are key enablers for OCDMA systems. Employing these integrated ring-resonator devices, we experimentally investigated a coherent OCDMA scheme based on spectral-phase encoding and decoding of mode-locked pulses. A multiuser synchronous OCDMA system is shown to operate at BER $< 10^{-9}$ with a spectral efficiency of 25% for data rates of 2.5 Gb/s. A single programmable decoder allows the correct decoding of any of the four users with high fidelity. Future efforts are directed at increasing the number of users, data rate, and the overall spectral efficiency.

Programmability in the coders is another noteworthy feature and offers the potential to enhance the flexibility and reconfigurability of networks by enabling network applications and functions such as addressing and routing through optical code translation. Furthermore, the narrow spectral bandwidth occupied by each user makes it compatible with existing WDM systems, allowing the possibility of an overlay architecture with spectral-phase-encoded OCDMA within a tunable DWDM window.

Finally, we note that besides their use in the application we have demonstrated, ring resonators are highly suitable for the future integration of optical functionalities including optical filtering, modulation, and switching. These microring resonators, combined with high levels of optical integration are important enablers of optical-signal-processing technology.

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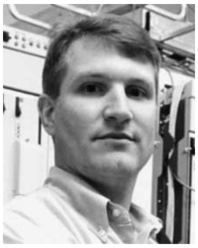
Dr. Jackel is a Fellow of the Optical Society of America (OSA).



**Jeffrey Young** joined Bellcore in 1985 and has been a member of Technical Staff in the optical communications research organization with Telcordia for 20 years. His area of expertise include network-element subsystem design and integration, optical system packaging of delicate passive and active fiber-optic components into subsystems for research and dense-wavelength-division-multiplexing (DWDM) systems testing. He has worked with numerous DWDM technologies, including erbium-doped fiber amplifiers (EDFAs), photonic switching, optical cable and connectorization, laser transmitters, receivers, and arc fusion splicing of standard and polarization-maintaining fiber. He has been involved in various optical networking projects including Optical Networks Technology Consortium (ONTC) and Multiwavelength Optical NETwork (MONET) where he was responsible for systems integration and network control and management signaling for a ten-node ring.

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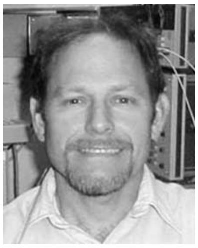

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**B. E. Little**, photograph and biography not available at the time of publication.

**S. T. Chu**, photograph and biography not available at the time of publication.

**Wei Chen**, photograph and biography not available at the time of publication.

**Wenlu Chen**, photograph and biography not available at the time of publication.

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**D. Gill**, photograph and biography not available at the time of publication.

**O. King**, photograph and biography not available at the time of publication.

**R. Davidson**, photograph and biography not available at the time of publication.

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After obtaining the Ph.D. degree, he joined Bell Communication Research as a member of the Technical Staff, where he concentrated his efforts towards generating ultrafast high-power optical pulses from semiconductor diode lasers, for applications in applied photonic networks. Some of his technical accomplishments were the development of the world's fastest most powerful mode-locked semiconductor laser diode, the demonstration of an optically distributed clocking network for high-speed digital switches and supercomputer applications, and the first observation of the optical nonlinearity induced by the cooling of highly excited electron-hole pairs in semiconductor optical amplifiers. He joined the faculty at the School of Optics and the Center for Research and Education in Optics and Lasers (CREOL), University of Central Florida (UCF), Orlando, in 1993, and currently holds the positions of University Trustee Chair Professor of Optics, ECE & Physics. He has published over 275 articles in refereed journals and conference proceedings, and has been awarded 12 U.S. patents.

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