Coherent Spectral Phased Coded OCDM Systems: Progress in Spectral Efficiency and Long-Distance Transmission

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***Abstract*—We review recent developments in coherent, spectral phase coded optical code-division multiplexed (OCDM) systems employing integrated ring-resonator based coding technologies. We describe progress in advanced modulation formats for improved spectral efficiency and long distance transmission.**

I. Introduction

In recent years, considerable progress has been made in the development of stable, multi-frequency phase-locked optical sources, including those based on mode-locked and externally-modulated comb generation techniques. At the same time, advances in integrated photonic device technologies that have the ability to access and modify the optical phase of signals with high spectral resolution are allowing for increasingly complex signal processing in the optical domain. One area that has benefited considerably from these technological advances is *optical code-division* technologies [1], including application to multiple-access (OCDMA) and multiplexing (OCDM) systems.

In this paper, we focus on one particular implementation of coherent OCDM systems based on spectral phase coding [2, 3] that is specifically designed to provide high spectral efficiency [4], allowing for compatibility with conventional dense wavelength division multiplexing (DWDM). In addition to providing a system overview and describing some of the enabling technologies, we discuss some of our recent efforts enabling increased spectral efficiency and longer transmission distances. These results demonstrate the increased ability of such narrowband OCDM systems to coexist with more conventional DWDM signals within a wide area networking environment carrying. We also briefly discuss some of the more advanced networking applications that OCDM can potentially enable beyond simple multiplexing, including providing a mechanism for securing the digital stream of 1's and 0's at the photonic layer through techniques such as shared code scrambling.

II. Narrowband Spectral-Phase-Coded OCDM

The block diagram of the spectral-phase-coded system is shown in Figure 1. A coherent multi-wavelength laser source (typically a mode-locked laser (MLL) or externally-modulated comb source) provides an equally-spaced set of N phase-locked optical frequencies. The coherent sum results in a periodic pulse train in the time domain, which is then modulated with digital data originating from individual OCDM channels or tributaries. The use of a coherent multi-wavelength source here allows for a variety of optical modulation formats to be implemented, including those based on amplitude and/or phase. After modulation, which results in a broadening of the discrete frequency components, a spectral phase encoder applies a phase mask to the entire set of broadened lines. The encoding leaves the set of frequency amplitudes unaltered, shifting only their relative phases, but temporally spreads the waveform. The encoded optical channel is passively combined with the remaining N-1 tributaries, each of which has its own unique orthogonal (e.g., Hadamard) spectral phase code [1]. Finally, a shared encoder, referred as a scrambling in Figure 1, is applied to the aggregate signal for signal confidentiality [5].

After tributary multiplexing, the aggregate OCDM

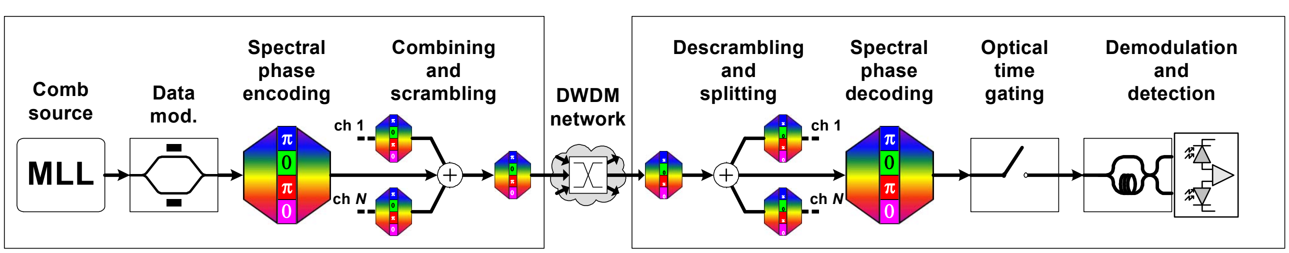

Fig. 1 Block diagram of coherent spectral-phase-coded OCDM system.

signal can be carried over an optically-transparent path to its destination, whereby one or more tributaries can be decoded, recovering the original data stream. As illustrated in Figure 1, the incoming signal is first code-descrambled (which applies a phase mask that is the complex conjugate of the code scrambler) and optical power is passively split between N tributary decoding elements. The decoding realigns the spectral phase for each particular tributary, recreating the original short pulse. Through the use of synchronized transmission and optically-orthogonal coding, signal energy from the remaining N-1 tributaries can be forced to lie in a temporal region outside the optically-gated pulse interval. Finally, optical demodulation and optical-to-electrical conversion recovers the original digital data stream.

III. INTEGRATED OCDM DEVICE TECHNOLOGIES

As with all OCDM/OCDMA systems, a key component is the encoding/decoding element. In our OCDM system, it enables much of the needed functionality including spectral phase encoding, code scrambling, code descrambling, and finally spectral phase decoding. Given the symmetry present in the OCDM systems, the same element used for transmitter encoding can often be used to implement decoding at the receiver. In addition, it turns out that the shared code scrambling (descrambling) steps mentioned above can be folded into the encoder (decoder) phase masks at the transmitter (receiver), resulting in fewer physical devices.

Another important consideration for practical OCDM systems is the ability to reconfigure the system, which allows for code-based switching [6], which would be equivalent to wavelength-based switching in DWDM systems. In addition, for our particular system, programmable coders allow for the scrambling/descrambling matrices to be periodically updated. We have developed programmable spectral phase coders based on micro-ring resonators, which have the advantage of high spectral resolution as well as scalable photonic integration.

Figure 2 illustrates our N-stage spectral phase encoder/decoder architecture based on 4-ring micro-ring resonator channel filtering. The coder demultiplexes individual frequency bins, applies relative phase shifts between adjacent bins, and recombines onto a single waveguide bus. Also shown for reference in Figure 2 is a fabricated 16-bin coder, highlighting the extremely small dimensions possible in integrated SiO_2/Si technologies [7].

IV. ADVANCED MODULATION FORMATS FOR OCDM

While much of the research on OCMA/OCDM systems to date has focused on conventional on-off keyed (OOK) modulation formats, one of the benefits of coherent systems is the ability to employ complex modulation formats. Some of these more advanced modulation formats include differential phase shift keying (DPSK), which can improve system tolerance to certain forms of interference noise [8], and differential quadrature shift keying (DQPSK), which can increase overall spectral efficiency of the OCDM system. By combining DQPSK with forward-error correction, we have experimentally demonstrated an 80 Gb/s aggregate OCDM signal (8-tributaries x 10 Gb/s) operating within a narrow 80 GHz bandwidth for a spectral efficiency of 0.87 b/s/Hz [9]. In addition, we have leveraged DPSK modulation to achieve a record transmission of a 40 Gb/s aggregate OCDM signal (8-tributaries x 5 Gb/s) over 400km within an 80 GHz bandwidth [10], while simultaneously employing quaternary spectral code scrambling to provide for confidentiality [5] of the 40 Gbs/ data stream.

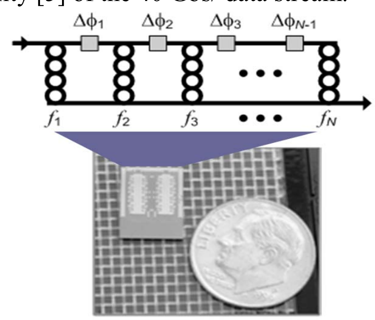

Fig. 2 Micro-ring resonator based spectral phase encoder

IV. SUMMARY

We have provided a summary of recent developments in the area of coherent, spectral-phase-coded OCDM systems based on integrated micro-ring resonator device technologies. Significant advances have been made both in the underlying technologies, such as enhanced code scrambling techniques and programmable coders, as well as increased system performance, including spectral efficiency approaching 1 b/s/Hz and fiber transmission up to 400 km.

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