SPECTS O-CDMA 80.8-km BOSSNET Field Trial using a Compact, Fully Integrated, AWG-Based Encoder/Decoder

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Abstract: We demonstrate successful encoding and decoding of SPECTS O-CDMA signals using a compact, fully integrated, AWG-based encoder/decoder. The signal is recovered in the presence of an interferer after transmission across an 80.8-km BOSSNET link.

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1. Introduction
As demand for broadband access increases, service providers are increasingly looking toward access schemes that allow for high speeds while maintaining flexibility, reconfigurability, and simplified network control and management. Optical code-division multiple-access (O-CDMA) has long been a possible candidate to provide these needs, and recent realization of fiber-to-the-premise (FTTP) has renewed interest in O-CDMA. Among various O-CDMA schemes, spectral phase encoded time-spreading (SPECTS) has shown extreme promise, with recent demonstrations showing successful recovery of 10 Gb/s signals in the presence of up to 31 interfering signals [1]. This scheme applies a phase code to the spectrum of data-modulated pulses, causing the signal to spread out in time. The signal is recovered only when a decoder applies the conjugate phase code, resulting in an autocorrelation peak. In a multi-user system, each user is assigned their own phase code, and a thresholder at the receiver separates the desired signal from the other transmissions, which remain spread in time by virtue of code orthogonality. Most SPECTS O-CDMA implementations have been limited by their dependence on cumbersome bulk optics-based encoders and decoders [1, 2], reducing their practicality in rigorous telecom environments. SPECTS O-CDMA implementations using integrated components have thus far been limited to short code lengths (up to 8 chips) leading to low signal-to-interferer contrast [3], or have been unable to incorporate components onto a single monolithic device [4]. In this paper, we present a SPECTS O-CDMA system utilizing a compact, monolithic, fully-integrated encoder/decoder based on polarization-independent, silica arrayed waveguide grating (AWG) technology. The device supports code lengths of up to 64 chips, enabling signal-to-interferer contrasts that far exceed previous monolithic devices. The contrast achieved enables successful encoding and decoding of a signal in the presence of an interferer after being transmitted over an 80.8-km link within the Boston South Network (BOSSNET).

2. Field Trial Description
The set-up for the field trial is shown in Fig. 1, where key components include the optical frequency comb generator (OFCG), integrated SPECTS O-CDMA encoder/decoder, tunable dispersion slope compensator, BOSSNET field fiber, and O-CDMA receiver. Pulses for the system originate from the OFCG [5] cascaded with a pulse compressor (dispersion decreasing fiber), producing over 120 optical comb lines spaced at 20 GHz. Temporally, this produces pulses with a full-width at half maximum (FWHM) of ~650 fs. 2.5-Gb/s data modulated pulses are sent to the integrated SPECTS O-CDMA encoder/decoder, which consists of two multiport AWGs interspaced by an array of phase modulators. Each AWG has passbands spaced 20 GHz apart, and the comb source is tuned to align its modes to filter through the passbands. As an encoder, the first AWG acts as a wavelength demultiplexer for the incoming signal, sending each incoming mode on to one of the phase modulators, which applies either a 0 or π phase shift on the individual mode as specified by the code, a 63-chip m-sequence. The phase-modulated modes are then wavelength multiplexed back together using the second AWG, producing an encoded pulse. A unique feature of the encoder/decoder is its ability to simultaneously encode multiple signals simply by sending them into different input ports of the first AWG (a total of four out of a possible sixteen input ports are available for this). The signals will exit from the second AWG on their own unique output port with minimal crosstalk from other channels, and they will be encoded with a bit-shifted version of the initial m-sequence. For the field trial, we obtain two uniquely
encoded signals by splitting the modulated comb source between input ports labeled 1 and 5. Attenuators (att.) and
time delays in the path of port 5 ensure power equalization and bit pattern decorrelation with the signal of port 1.
The signals are combined and sent through the field fiber, which consists of an 80.8-km (40.4 km one-way)
BOSSNET link that originates from Massachusetts Institute of Technology Lincoln Laboratory (MIT-LL) in
Lexington, MA, traverses to a point-of-presence (POP) in Boston, MA, and loops back to MIT-LL. The link
consists largely of LEAF™ fiber and dispersion compensating fiber (DCF). Additional DCF applied after the link
compensates for 27.95 ps/nm of residual dispersion at 1550.4 nm, and a remaining 6 ps/nm² of dispersion slope is
precompensated using a tunable dispersion slope compensator consisting of a bulk optics-based pulse shaper with a
flexible mirror placed at the Fourier plane [6]. The flexible mirror is shaped as a cubic function capable of
continuously compensating -5.5 ps/nm² to 5.5 ps/nm² of dispersion slope. Upon return from the field fiber, the
signals are decoded by simply passing the signals through the device in the reverse direction by way of circulators
(circ.). The reapplication of the phase codes cause any π phase-shifted modes to return to a 2π (or 0-equiavelent)
phase shift, thereby restoring the pulse for the desired signal. For the field trial, signals are sent through port 1,
effectively recovering the signal encoded from port 1 while leaving the signal encoded from port 5 incorrectly
decoded (this becomes the interferer). The decoded signals are then sent into the O-CDMA receiver, which contains
a nonlinear thresholder to separate the interferer, followed by an optical-to-electrical (O/E) converter with data and
clock recovery.

3. Results and Discussion

The operation of the O-CDMA encoder/decoder is demonstrated in Fig. 2a, which shows autocorrelations of
the correctly decoded signal and the incorrectly decoded interferer on a back-to-back transmission. The correctly
decoded signal produces a 1.0-ps wide pulse while the incorrectly decoded interferer remains spread, appearing as a
pseudonoise burst with a temporal width exceeding 50 ps. The peak intensity of the interferer is approximately 11
times smaller than the peak of the correctly decoded signal. The integrity of the pulse shape is well maintained after
transmission through the BOSSNET link (Fig. 2b), due to the careful dispersion compensation. The pulse width of
the correctly decoded pulse after transmission spreads to only 1.3 ps. Fig. 2b also shows the autocorrelation of
original pulse generated by the comb source, and this has a width of 650 fs. The spreading after encoding and
decoding arises primarily from the spectral filtering applied by the encoder/decoder.

To characterize system performance, we measure both the response of the nonlinear thresholder and the bit-
error-rate performance. The nonlinear thresholder operates by amplifying incoming signals such that a correctly
decoded signal, with its high peak power, will generate additional spectrum at shorter and longer wavelengths as it
propagates down highly nonlinear fiber (HNLF) by virtue of self-phase modulation. This energy can then be filtered
out and sent into an O/E converter. Thresholding occurs because an incorrectly decoded signal with much lower
intensity levels will be unable to generate the same nonlinear response despite amplification. As a result, the
incorrectly decoded signal will not produce enough energy to significantly pass through the filter to be detected by
the O/E converter. The proper behavior of the thresholder is demonstrated in Fig. 3a, which shows the spectrum
generated by the signals at the output of the thresholder’s HNLF, after traversing the 80.8-km link. The interferer
produces very little nonlinearity such that most of the interferer’s spectrum is contained within 5 nm of the central
wavelength (1550 nm). The correctly decoded signal, on the other hand, can generate spectral components shorter
than 1540 nm and longer than 1560 nm. When both signal and interferer are present at the thresholder (a two-user
system), the spectrum at the shorter and longer wavelengths expectedly appears similar to the one produced by the
signal by itself, as the majority of the power at these wavelengths is contributed by the signal. Thus for optimum
discrimination of the interferer, the 3-nm bandwidth filter of the thresholder is tuned to 1559 nm, as shown. For
back-to-back transmission, it is necessary to tune the filter to 1561 nm, as the absence of the BOSSNET link results
in less dispersion, and therefore more generation of spectral components at longer wavelengths. For consistency, the
position of the filter is kept unchanged when switching from a two-user system to a one-user system, which contains
the correctly decoded signal only. Bit-error-rate and eye diagram performance of the system is shown in Fig. 3b
using a pseudorandom bit sequence (PRBS) length of $2^{31}-1$ bits, where the received power/user indicates the power
of each user measured at the input of the O-CDMA receiver module. For this measurement, the delay of the
interferer was tuned so as not to coincide with the signal in order to minimize coherent beat interference (a time-
slotted system [3]). Because the thresholder filter is optimized for the two-user case, there is actually a slight power
penalty (< 1dB @ BER=10⁻⁹) when going to the one-user case for back-to-back transmission. For 80.8-km
transmission, there is an expected power penalty going from one to two users for lower powers, but the curves
eventually converge. The BER curve of the one-user case may be an indication that the peak powers of the signal
fall within the transition point of the thresholder, the range where a signal pulse transitions between being
suppressed to being passed by the thresholding filter. Nonetheless, the BER curves still achieve BER < 10⁻⁹.

![Fig. 2. (a) Autocorrelations of the correctly decoded and incorrectly decoded signals for back-to-back transmission. (b) Autocorrelation of the
correctly decoded signal after the 80.8-km fiber transmission link. (c) Nonlinear thresholder response. (d) BER results with eye diagrams.](a1546_1.pdf)

4. Conclusion
We have demonstrated a SPECTS O-CDMA system utilizing a compact, integrated encoder/decoder. The device is
capable of encoding and decoding multiple signals simultaneously and supports coding lengths of up to 64-chips.
The improved signal-to-interferer ratio obtained with the longer codes enables the system to perform with BER<10⁻⁹
in the presence of an interferer after traversing through 80.8 km of field fiber.

5. References

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