Spectrally coded O-CDMA system with four users at 2.5 Gbit/s using low power nonlinear processing

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A four-user 2.5 Gbit/s optical code-division multiple-access (O-CDMA) system is demonstrated at $\leq 10^{-11}$ BER utilising programmable spectral phase encoding, an ultrasensitive (<0.4 pJ/bit) PPLN-waveguide nonlinear waveform discriminator, and a 10G Ethernet receiver.

Introduction: Optical code-division multiple-access (O-CDMA) is receiving increasing attention owing to its potential for enhanced information security, simplified and decentralised network control, improved spectral efficiency, and increased flexibility in the granularity of bandwidth that can be provisioned. In many O-CDMA approaches, input ultrashort pulses are time-spread during the encoding process into lower intensity noise-like signals [1–6]. In the receiver, data corresponding to a desired user is separated from multi-access interference via a matched filtering (decoding) operation. Since the energy in properly and improperly decoded signals is similar, and since the temporal duration of even improperly decoded signals is of the order of the bit period or below, both properly and improperly decoded signals will appear identical to an electronic receiver band-limited to the data rate. Consequently either very fast electronics or a nonlinear optical intensity discriminator play a critical role in separating properly decoded short pulses from improperly decoded multi-access interference. In previous work, most discriminators were based on fibre optics, which required high power [2–4], and very few tests with multi-user interference were reported [2]. An O-CDMA/WDM/TDM overlay experiment demonstrated very high aggregate bit rates, but relied on synchronous nonlinear gating in the receiver, with synchronism required down to ~1 ps [2]. In this Letter we discuss a four-user spectral-phase-encoded O-CDMA demonstration at 2.5 Gbit/s with strong nonlinear interference suppression. Compared to previous work, the key points are the following: (i) full interference suppression with four users at Gbit/s rates without the need for synchronous gating; (ii) the use of a novel, ultrasensitive nonlinear optical intensity discriminator based on second-harmonic generation (SHG) in a periodically-poled lithium niobate (PPLN) waveguide. Our discriminator permits a suppression as high as 20 dB at an operating pulse energy of <0.4 pJ (average power <1 mW), approximately two orders of magnitude lower than previous discriminators based on nonlinear fibre optics [3, 4]. The ability to operate at low power per user is critical for scaling O-CDMA to greater numbers of users. In multi-user networking each receiver will see a sample of each of the multiple-access signals; therefore, the required amplifier saturation power scales with the number of users (as well as bit rate).

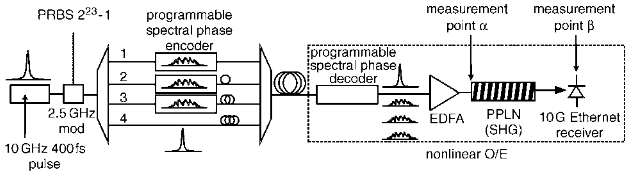

Fig. 1 *Four-user O-CDMA system testbed*

Experiments and results: A schematic diagram of the four-user O-CDMA demonstration is shown in Fig. 1. An actively modelocked fibre laser followed by a dispersion decreasing fibre soliton compressor producing nearly transform-limited ~0.4 ps pulses at ~10 GHz centred near 1542 nm is used as the pulse source. A 2.5 Gbit/s PRBS 2^{23}-1 data stream is impressed on the laser output with an intensity modulator and then a 1 × 4 passive splitter is used to generate the four separate users. For three users, the modulated ultra-short pulses are input into fibre coupled Fourier transform pulse shapers [7] which incorporate a 128-element liquid crystal modulator array to spectrally phase code the spectrum of the source laser. The fibre-to-fibre insertion loss of the pulse shapers is <5 dB. A fourth uncoded user path is also present as an additional strong interference channel. The output of each user path is connected through a fibre delay line to a 4 × 1 combiner and then connected to the transmission fibre consisting primarily of DCF used to compensate the dispersion of the user paths. The receiver consists of a fibre coupled Fourier transform pulse shaper used to select the user channel to decode, an optical amplifier, a highly sensitive fibre pigtailed PPLN waveguide chip to perform the nonlinear discrimination function [8], and a 2.4 GHz bandwidth photoreceiver, adapted from 10 Gbit/s Ethernet, operating at the second-harmonic wavelength of 0.77 µm. The measured SHG efficiency of PPLN is 3.1%/mW for continuous-wave (CW) and 170%/pJ for ultra-short pulses.

Fig. 2 demonstrates the ability to properly decode any of the four-user channels by the correct selection of decoder spectral phase code – here a length 31 M-sequence code. The Figure shows intensity cross-correlation measurements of the non-data-modulated stream measured at 'measurement point α' (just before the nonlinear processor) shown in Fig. 1. The advantage of a nonlinear pulse discriminator is dramatically demonstrated in Fig. 3. Fig. 3*a* shows the temporal profile of four overlapping users at 'measurement point α', with one user properly decoded (channel 1) and other three users improperly decoded, where we use a 1.5 µm photodetector optimised for the 2.5 Gbit/s data rate to detect the decoder output prior to entering the nonlinear processor. The eyes are completely closed. This clearly illustrates the main issue in O-CDMA with ultra-short pulses: properly decoded and improperly decoded waveforms have fundamentally the same energy, which means they produce the same output from a relatively slow electronic detector, even though they can show strong differences in temporal structure and peak intensity on an ultrafast time scale (as per Fig. 2). In a system environment, the signals from all users will be superimposed when viewed by a conventional photoreceiver with bandwidth optimised for the data rate.

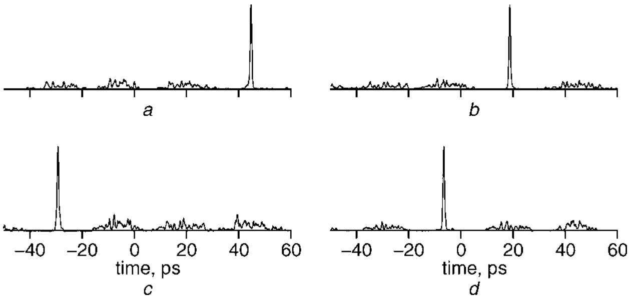

Fig. 2 *Intensity cross-correlation measurements of properly decoded channels 1 to 4 (Figs. a to d, respectively) demonstrating the ability to selectively decode any of the four-user channels*

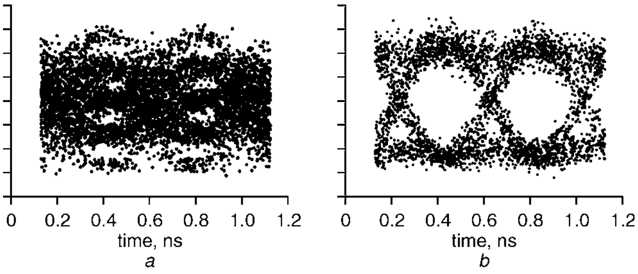

Fig. 3 *Eye diagrams for four users at −3 dBm per user*

a Prior to nonlinear processing (measurement point α in Fig. 1)
b After nonlinear processing (measurement point β in Fig. 1)

Nonlinear processing enables us to separate these temporally overlapped signals thereby permitting a multi-user system. Fig. 3*b* shows four-user output of the receiver (measurement point β in Fig. 1), with one user properly decoded (channel 1) and the other three users improperly decoded at a power in the nonlinear processing element of −3 dBm per user. The clean eye diagram clearly demonstrates the ability to properly decode the desired channel, and separate it from the interference channels. Figs. 4*a* and *b* show bit error rate curves for one, two and four users plotted against power at the photoreceiver ('measurement point β'), with either channel 1 or 2 decoded. In all cases we were able to measure BERs down to $<10^{-11}$. There is a power penalty of roughly 1.5 dB per interfering user (similar for both decoded channels) which we attribute to the finite interference suppression ratio of the nonlinear discriminator. Fig. 4*c* shows the same BER data as in Fig. 4*a*, but replotted against the total power in the nonlinear discriminator ('measurement point α'). The key point is that we are able to run the four-user experiment at under 1 mW per user in the nonlinear element, which provides substantial margin for scaling to higher bit rates and user counts while provisioning only a moderately sized optical amplifier to each receiver node.

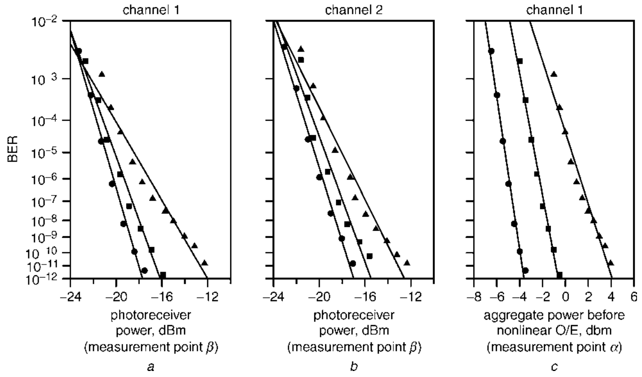

Fig. 4 *Bit error rate measurements for single user (circles), two users (squares), four users (triangles)*

a Channel 1 decoded
b Channel 2 decoded
c Same as *a* but now power refers to value in nonlinear waveguide
System operated at < 1 mW per user

Conclusion: We have demonstrated a multi-user O-CDMA system operating at 2.5 Gbit/s requiring less than 0.4 pJ/bit per user due to the novel nonlinear processing element based on SHG in a PPLN waveguide.

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