5 SOTO-CRESPO, J.M., WRIGHT, E.M., and AKHMEDIEV, N.N.: 'Recurrence and azimuthal-symmetry breaking of a cylindrical Gaussian beam in a saturable self-focusing medium', *Phys. Rev. A*, 1992, **45**, pp. 3168–3175
6 TIKHONENKO, V., CHRISTOU, J., and LUTHER-DAVES, B.: 'Spiraling bright spatial solitons formed by the breakup of an optical vortex in a saturable self-focusing medium', *J. Opt. Soc. Am. B*, 1995, **12**, pp. 2046–2052

Nonlinear fibre-optic receiver for ultrashort pulse code division multiple access communications

H.P. Sardesai and A.M. Weiner

Indexing terms: Optical receivers, Multi-access systems, Optical communication

The authors present experimental results on a nonlinear optical receiver for ultrashort pulse code division multiple access communications which uses nonlinear frequency shift effects in optical fibres to perform intensity discrimination with femtosecond response times. The receiver exhibits a contrast ratio of nearly 1000 for received pulse energies of ~1pJ.

Optical code division multiple access (CDMA) communication systems are an interesting choice for local area optical networks due to their unique attributes of optical processing, asynchronous transmission, high information security and multiple access capability [1]. In a previously proposed optical CDMA scheme using coherent ultrashort pulses [1, 2], the CDMA transmitters would use a spectral phase encoder to convert input femtosecond pulses into low intensity pseudonoise bursts. Multiple-access would be accomplished by assigning different, minimally interfering phase codes to different users. Correctly coded signals are converted back into femtosecond pulses by a spectral phase decoder in the CDMA receiver, while incorrectly coded signals remain as low intensity pseudonoise bursts. The desired data can be then detected using a nonlinear optical thresholder. The key requirement for the ultrashort pulse CDMA receiver/thresholder is the ability to discriminate between properly decoded femtosecond pulses and the equally energetic but improperly decoded picosecond interference signals. In this Letter we report on a nonlinear fibre-optic receiver for an ultrashort pulse optical CDMA system which uses intensity dependent nonlinear frequency shift effects in optical fibres to achieve thresholding with a high contrast ratio approaching 1000.

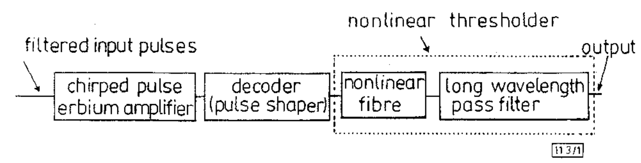

Fig. 1 *Block diagram of experimental arrangement*

A block diagram of the receiver is shown in Fig. 1. Input pulses to the experiment are generated by a stretched pulse modelocked fibre ring laser [3] and are spectrally filtered to yield pulse durations of ~275fs with a repetition rate of 31.2MHz, an average power 30µW and a bandwidth of ~11nm centred at ~1559nm. These pulses are amplified by a chirped pulse erbium doped fibre amplifier. In the amplifier, input pulses are first stretched by propagating them through 60m of standard singlemode fibre. They are then propagated through 26m of erbium doped fibre (Corning type II T-8533-301) which serves as the gain medium and are finally compressed by 13.4m of dispersion compensating fibre (AT&T fibre JR1DC1074C10C). When pumped by 130mW of pump power at 980nm, the amplifier exhibits a gain of ~29dB and an output power of ~20mW. Gain narrowing in the amplifier broadens the pulses to between 350 and 500fs with a corresponding spectral bandwidth of 6–8nm centred at 1559nm. At output powers higher than ~5mW, in addition to gain narrowing we see some small nonlinear effects in the compressed pulses as evidenced by some broadening at the base of the pulses in the autocorrelation traces. Overall, the output pulses are close to distortion free with measured FWHM time-bandwidth products between 0.32 to 0.36 for output powers between ~4 to ~15mW. The amplified pulses are then passed through a fibre pigtailed pulse shaper containing a 128 element liquid crystal phase modulator (LCM) which acts as a programmable spectral encoder [4]. As demonstrated before [4], in the pulse shaper, the LCM is used to set the spectral phases either to a length 63 M-sequence pseudorandom phase code (which encodes the pulses into 10–12ps wide pseudorandom bursts) or held constant (leading to 600–800fs uncoded pulses). For *M*-sequence bits equal to 1, the phases of the corresponding LCM pixels are set to π radians; for bits equal to zero, the phase is set to 0 radians. The entire *M*-sequence is accommodated by the LCM with two pixels of the LCM corresponding to every bit of the *M*-sequence. The insertion loss of the entire pulse shaper from the input fibre to the output fibre is ~8.8dB. For a full CDMA system consisting of an encoder and a decoder, the coded pulse here would correspond to an improperly decoded signal in the full system; the uncoded pulses would similarly correspond to properly decoded pulses in the full system. Although ideally a pulse shaper should cause no temporal pulse broadening when a constant phase is applied to the LCM [4], we do observe some broadening for the uncoded pulses here; the cause of this broadening is currently under investigation.

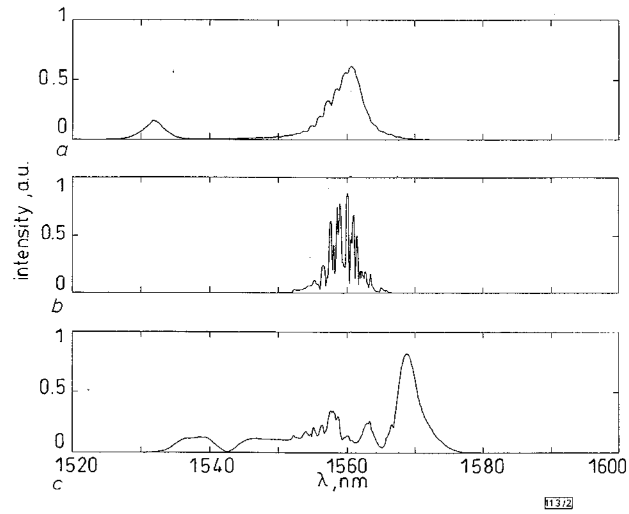

Fig. 2 *Power spectra*

a At input of decoder
b Coded signal (which would be equivalent to improperly decoded signal for full system with both encoders and decoders) at output of thresholder
c Uncoded signal (which would be equivalent to properly decoded signal for full system with both encoders and decoders) at output of thresholder
Average power at input of receiver is 30µW and average power at input of nonlinear thresholder fibre is 0.44mW for *b* and *c*

Coded or uncoded pulses from the pulse shaper are connected to the nonlinear thresholder which is simply a 500m length of dispersion shifted optical fibre with zero dispersion wavelength λ_0 = 1559nm (which is near the centre of the amplified spectrum) followed by a longpass filter and photodetector. Nonlinear propagation effects cause the spectrum of the uncoded pulse to split and spread to either side of λ_0 [5, 6]. The magnitude of the spectral split can be controlled by varying the intensity and time duration of the pulse and the propagation distance through the fibre. The coded pulse with a lower intensity and larger time duration propagates through the same length of the thresholder fibre but exhibits negligible spectral shifts. Figs. 2*b* and *c* shows the power spectral data for 0.44mW average power in the thresholder fibre clearly revealing the differences in the output spectra for coded and uncoded pulses. The power spectrum at the input of the decoder is also shown for comparison in Fig. 2*a*. Please note that the emission at 1530nm and the long wavelength tail at 1570nm of the amplifier output spectrum are suppressed in the pulse shaper due to the finite aperture of the pulse shaper optics. These frequency shifts are converted into a contrast in energy by using a long wavelength pass filter followed by a conventional photodetector operating at speeds comparable to the repetition rate of the system. By optimally choosing the average power and the filter cutoff wavelength, a high contrast ratio is obtained. The contrast ratio is defined as the ratio of the energy of the uncoded pulses to that of the coded pulses at the output of the thresholder. As seen in Fig. 3, a contrast ratio of nearly 1000 is achieved for a 1569nm cutoff wavelength, a 0.44mW average power for a fixed *M*-sequence code. It should be noted that the higher contrast ratio at longer cutoff wavelengths comes at the expense of lower energy at the output of the thresholder. Fig. 4 shows the conversion efficiency of the nonlinear thresholder defined as the ratio of the energy at the output of the thresholder to the energy at the input of the thresholder. As shown in the Figure, for 0.44mW average power at the thresholder input, we get almost 50% conversion efficiency for lower cutoff wavelengths, but the efficiency drops down to ~10% when the cutoff wavelength is ~1569nm.

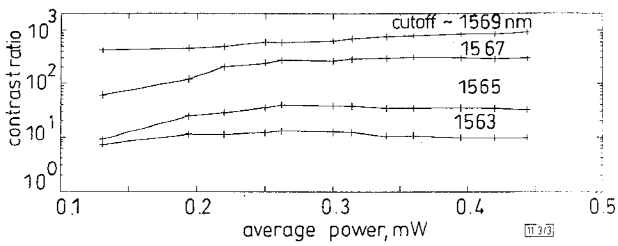

Fig. 3 *Contrast ratio of nonlinear receiver for different cutoff wavelengths of long wavelength pass filter against average signal power at input of nonlinear thresholder fibre*

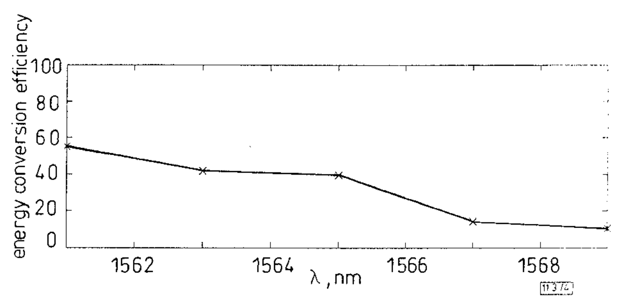

Fig. 4 *Energy conversion efficiency of nonlinear thresholder for different cutoff wavelengths of long wavelength pass filter*

Average signal power at input of thresholder fibre is 0.44mW

In conclusion we have demonstrated a nonlinear fibre optic receiver for ultrashort pulse CDMA systems which can operate at received pulse energies as low as ~1pJ. The receiver has an internal erbium fibre preamplifier, a fibre pigtailed pulse shaper decoder, a passive fibre where nonlinear frequency shifts occur and a long wavelength pass filter. The receiver has a contrast ratio of nearly 1000 and a conversion efficiency of nearly 10%. In the future it should be possible to obtain even higher contrast ratios by including hard spectral apertures within the pulse shaper/decoder and to demonstrate similar thresholder concepts based on soliton self-frequency shifts in fibres with λ_0 at shorter wavelengths. We also intend to use these thresholders in system experiments testing ultrashort pulse CDMA systems over distances suitable for local area networks.

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References

1 SALEHI, J.A., WEINER, A.M., and HERITAGE, J.P.: 'Coherent ultrashort light pulse code-division multiple access communication systems', *J. Lightwave Technol.*, 1990, **8**, (3), pp. 478–491
2 WEINER, A.M.: 'Femtosecond optical pulse shaping and processing', *Progress in Quantum Elect.*, 1995, **19**, (3), pp. 161–237
3 TAMURA, K., IPPEN, E.P., HAUS, H.A., and NELSON, L.E.: '77-fs pulse generation from a stretched-pulse modelocked all-fibre ring laser', *Opt. Lett.*, 1993, **18**, (13), pp. 1080–1082
4 WEINER, A.M., LEAIRD, D.S., PATEL, J.S., and WULLERT, J.R.: 'Programmable shaping of femtosecond optical pulses by use of a 128-element liquid crytstal phase modulator', *IEEE J. Quantum Electron.*, 1992, **28**, (4), pp. 908–920
5 AGRAWAL, G.P., and POTASEK, M.J.: 'Nonlinear pulse distortion in single-mode optical fibres at zero-dispersion wavelength', *Phys. Rev. A.*, 1986, **33**, (3), pp. 1765–1776
6 STERN, M., HERITAGE, J.P., ANDERSON, W.T., and KILMER, J.: 'Soliton technique to characterize single-mode fibre dispersion', *J. Lightwave Technol.*, 1992, **10**, (12), pp. 1777–1779

Reflection-type normally-on two-wavelength modulator

Chia-Ming Tsai and Chien-Ping Lee

Indexing terms: Semiconductor quantum wells, Optical modulation

The authors demonstrate a novel reflection-type normally-on two-wavelength modulator by combining two quantum-well structures with different operating wavelengths in a coupled cavity structure. Reflection spectra show simultaneous modulations at wavelengths of 856 and 886 nm in the device consisting of GaAs/AlGaAs and InGaAs/AlGaAs quantum wells for each wavelength. Under separate applied voltages, maximum reflectivity changes of 70 and 54% were obtained for the two wavelengths. To the best of the authors' knowledge, this is the first two-wavelength reflection modulator ever reported.

Surface-normal quantum well modulators based on quantum confined Stark effect (QCSE) have become one of the key devices in many applications, such as optical communications [1] and interconnections [2], optical switching networks [3], and optical data processing applications using e.g. smart pixels [4], because of their excellent performance and compatibility with other semiconductor optoelectronic devices. All the modulators developed so far are for single-wavelength operation. However, in future WDM or multichannel systems, transmission of multiple wavelengths is needed. Although multichannel laser diodes have been developed [5 – 9], modulators which are capable of handling two wavelengths or more have not been reported. In this Letter, we report for the first time a two-wavelength reflection-type quantum well modulator. We believe that this new device will provide much more flexibility for future system applications.

To achieve a two-wavelength modulator, two types of quantum wells with different operating wavelengths must be used simultaneously in one structure. But if these two modulators are put inside one simple conventional cavity, the quantum wells designed for long wavelength will absorb the short-wavelength photons, and the resonant condition cannot be tailored for both wavelengths. So, it is almost impossible to achieve a reasonable modulation performance. In our devices, a coupled-cavity design is used. The quantum wells for the short wavelength operation are placed in front of the quantum wells designed for the long wavelength and an additional reflector is placed in between to prevent short wavelength light penetrating into the lower quantum wells. For long-wavelength operation, another high-reflection mirror is added behind the long-wavelength quantum-well region to achieve a complete AFP cavity structure.

The two-wavelength modulator is shown as a schematic diagram in Fig. 1. It is similar to that of a coupled cavity modulator [10, 11]. But in our structure, we place the short-wavelength quantum-well absorbing layer in the front cavity. Because of the middle reflector and the large absorption coefficient of the quantum wells