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Pulse shaping, and pattern generation/recognition using fibre Bragg gratings

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Abstract: We describe two individual experiments concerned with controlling the shape of short pulses using superstructured fibre Bragg gratings (FBG's). In the first experiment 2.5 ps soliton pulses are reshaped into 20ps square pulses. In the second experiment, a 7-chip bipolar code is assigned to an incoming bit stream and the encoded pattern subsequently decoded using a second FBG acting as a matched filter. Transmission experiments of the encoded sequence are also described.

FBG's constitute an important passive element in today's all-optical fibre systems. Recent advances in their fabrication allow almost complete control of the amplitude and phase of the induced refractive index, broadening thus the range of potential applications. In the work presented here, FBG's are employed as controllable phase and amplitude filters, and are used for coherent manipulation of short pulses. The concept is that if we have a pulse of known phase and amplitude characteristics, by simple Fourier analysis we can design a filter to transform the input pulse to essentially any desired output pulse of specified phase and amplitude. For a weak FBG, i.e. one in which light penetrates its whole length without significant attenuation, its frequency response is given by the Fourier transform of the index modulation profile along the grating length. It follows directly that the impulse response of the grating is directly proportional to its refractive index profile, which as we pointed out previously can be controlled with high precision. The function used to modulate the refractive index of the FBG is its superstructure function. Consequently, a superstructured (or sampled) FBG can be designed, so that a given input signal can be shaped on reflection off the FBG according to any desired form. This technique offers tremendous potential for passive shaping and control of short optical pulses, as is required in several all-optical operations in optical fibre telecommunications systems. Its viability has been demonstrated in the past using simple [1, 2], or more sophisticated FBG structures [3]. Here we present two different experiments that progress the approach further, and perform respectively (a) shaping of 2.5ps soliton pulses into 20ps rectangular pulses, and (b) pulse encoding and subsequent matched filtering decoding, suitable for optical code-division multiple access (OCDMA) systems. Both experiments were performed at a bit rate of 10GHz, using the pulses provided by an actively and harmonically mode-locked erbium fibre ring laser [4]. This laser produced almost transform-limited soliton pulses of a width that varied with pump power from 2 - 4ps.

The grating designed for our first experiment was such that the product of its spectral electric-field response (amplitude and phase) with the spectrum of the incident soliton pulses is of a sinc-like form, yielding the required temporal reshaping. The overall grating bandwidth was limited to 6 nm to accommodate the full bandwidth of the 2.5ps soliton pulses down to -25 dB from the spectral peak. For our target 20 ps square pulses we can accommodate a total of 13 spectral lobes, with alternate optical phase. Note that the power spectrum of a perfect rectangular pulse (the sinc^2 function) extends to infinity either side of its main lobe. Using this reshaping approach we inevitably restrict the bandwidth. In order to avoid the ringing in the temporal domain that would otherwise ensue, we therefore apodized the output pulse spectrum (through the grating response) to smoothen the effects of this truncation. The reflected spectrum of the filter we designed is shown by the dashed line in fig. 1. The main features of the ideal sinc^2 power spectrum are still evident despite the apodisation, i.e. the zeros at every $1/T$ from the center frequency, where $T = 20$ ps, and the sidelobes of interchanging optical phase. The grating sampling function is given by the inverse Fourier transform of the grating's spectral response and is shown inset in fig. 1. Its full length in time is $t = 100$ ps, corresponding to a grating length of $0.5tc/n = 10.3$ mm, and consists of several sections of alternating phase. The grating was fabricated, using a continuous grating writing technique, based on grating plane by grating plane exposure [5]. The actual spectral response obtained is compared to the design in fig. 1 (solid line), and clearly demonstrates the quality and control provided by this writing technique. The temporal characteristics of the resultant pulses were measured with an autocorrelator. The autocorrelation of a rectangular pulse of duration T is a triangular pulse of full length 2T. The acquired autocorrelation trace is compared in fig. 2 to that of the incident pulses, and the calculated autocorrelation trace corresponding to the pulse shown inset. Once again the agreement is extremely good indicating excellent phase control within the grating.

The second experiment we describe relates to pulse encoding with a 7-chip binary bipolar sequence (i.e. phase encoding), and the subsequent decoding (or recognition of the pattern) using a matched FBG filter to the encoder. The bipolar pattern was encoded on the refractive index modulation of the FBG's by imposing π-phase shifts at certain points within the structures. Thus, the encoder FBG would assign this particular binary sequence to a short pulse (ideally an impulse) incident upon it. On the other hand, the signal reflected off the decoder FBG is the cross-correlation of the input pattern and the binary sequence written within the FBG. When these two waveforms match, an intense output is generated, otherwise a low amplitude signal is reflected back. This is the basic operation of any CDMA system. The binary pattern used to modulate the gratings' refractive indices was the m-sequence 111-1-11-1. This particular sequence was used, since it provides a single-peak autocorrelation function. Each chip was 0.66mm long resulting in an overall FBG length L = 4.64mm. This corresponds to a chip duration of 6.4ps and an overall duration for the code of 2Ln/c = 44.8ps. We fed 2.0ps soliton pulses (generated from the mode-locked laser) on the individual encoder/decoder FBG's and examined the intensity autocorrelation functions of the reflected signals, which we found to be in excellent agreement with our theoretical predictions. In fig. 3 we plot the experimental and theoretical intensity autocorrelation functions of the decoder response to the incident code pattern. The agreement is seen to be excellent. We also transmitted the encoded pattern over 25km of standard fibre, compensating for the dispersion of the line using a chirped FBG. An autocorrelation trace of the decoded sequence after transmission is also shown in fig. 4. We performed BER measurements on the coding/decoding process both with and without the 25km transmission. The results are summarised in fig. 4, where it is seen that no power penalty associated with the code/decode process is observed in either instance. Eye diagrams for both the simple code/decode and transmitted code/decode case (detected using a 20GHz photodiode) are shown inset within fig. 4. As expected no evidence of temporal features away from the main, chip-length long, correlation peak is observed.

In conclusion, we have demonstrated the use of weakly written FBG's for coherent control of short optical pulses in two different experiments. In the first, a 20ps square-pulse stream was generated by spectral filtering of the envelope of a 10GHz 2.5ps soliton-pulse stream, whereas in the second, all-optical pattern coding/recognition at 10Gbit/s was demonstrated. We believe these experiments to constitute a convincing demonstration of the role that superstructured FBG technology can play in several operations of future telecommunications networks.

References

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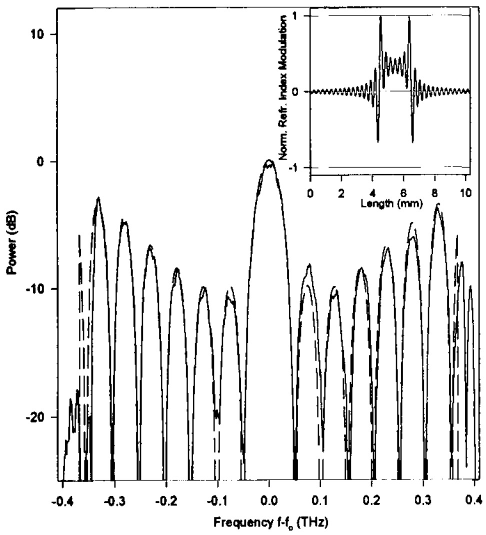

Fig. 1. Actual (solid line) and designed (dashed line) frequency response of the FBG for the generation of square pulses; the sampling function of the grating is shown in the inset.

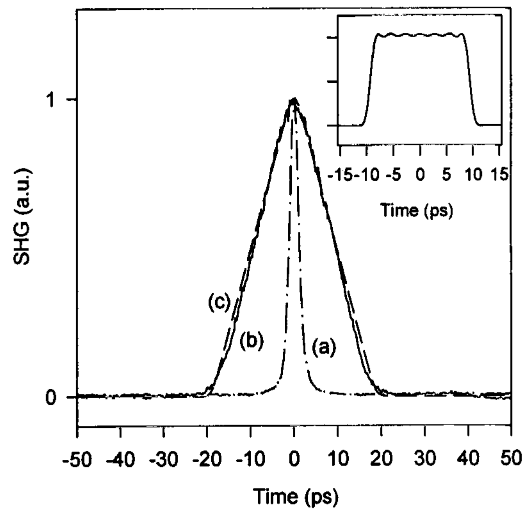

Fig. 2. Autocorrelation traces of the input 2.5 ps soliton pulses (a), and the output pulses (b). The dashed curve (c) corresponds to the calculated autocorrelation of the pulse shown in the inset.

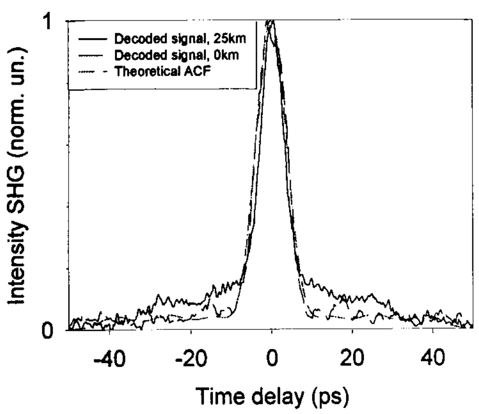

Fig. 3 Theoretical and experimental pulse intensity autocorrelation functions for the code:decode process both before and after transmission through 25km of (dispersion compensated) standard fibre.

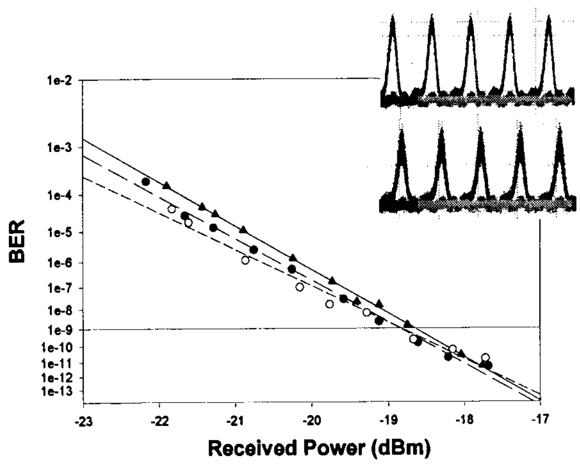

Fig. 4 BER curves for back-to-back (open circles), and decoded signal before (closed circles) and after (triangles) transmission; the corresponding eye diagrams are shown inset