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Applications of superstructured fibre Bragg gratings in OCDMA systems

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Superstructured fibre Bragg gratings enable the encoding and decoding of short pulses into long code sequences at ultrafast chip rates. Such code sequences can be used for the implementation of all-optical code division multiple access systems operating at Gbit/s data rates.

1. Introduction

The explosive growth of the Internet over recent years is placing increasing demands on both the capacity and functionality of optical communication systems. This is particularly the case in access networks where there is a clear requirement for broadband access techniques capable of supporting more than 100 independent optical channels, each operating at bit-rates of order 1 Gbit/s and above. Conventional optical multiplexing techniques, for example Dense Wavelength Division Multiplexing (DWDM) which has been applied with such success within core and metro networks, are likely to struggle from both a technological and economic perspective to achieve such fine channel granularity. The problems are compounded by the bursty-nature of packet based services such as the internet for which average data rates per user are frequently two orders of magnitude lower than the required peak rate. Provisioning of a dedicated wavelength channel per user makes for extremely poor spectral efficiency and associated high costs. There is thus great interest in alternative, more flexible, multiplexing techniques that might be more appropriate for this sort of environment and traffic.

Optical Code Division Multiple Access (OCDMA) is one such technique and seems far more suited to such applications. OCDMA promises a variety of attractive features for network operators relative to the more conventional WDM/OTDM and associated optical access techniques. These features include amongst others: asynchronous operation, flexible bandwidth management, improved system security and the potential for much higher levels of connectivity and network scalability. OCDMA is a spread spectrum technique similar to those that have been implemented with such great success in wireless communication systems. CDMA techniques allow a large pool of users to share the same transmission bandwidth. Each individual user, or sub-group of users, is allocated a specific address (code) that can be used to label bits that are either to be transmitted to the user, or to be transmitted by the user. The optical encoding is ordinarily performed either in the time domain (direct sequence DS-OCDMA), or in the frequency domain (frequency-hopping FH-OCDMA). Hybrid (also called two-dimensional or frequency-hopping) approaches have also been demonstrated. In DS-OCDMA each data bit to be transmitted is defined by a code composed of a sequence of individual pulses, referred to as chips. Coded bits are then broadcast onto the network and will only be received by users having a receiver designed to recover data bits encoded with that specific address. In FH-OCDMA, the carrier-frequency of the chips is changed according to a well-defined code sequence that can again be unambiguously identified by an appropriate receiver.

One of the key issues in OCDMA concerns the development of practical techniques that can be used to reliably generate and recognize appropriate code sequences. A variety of technical approaches to the coding/decoding process have been demonstrated to date including those based on spreading pulses in the time domain using for example arrays of fibre delay lines, planar lightwave circuits, or arrays of fibre gratings. Recently, however superstructured fibre Bragg grating (SSFBG) technology has emerged as an attractive and highly flexible route to produce high performance and potentially low-cost optical coders and decoders for DS-OCDMA.

2. SSFBGs for pulse encoding and decoding

Fibre Bragg gratings have found widespread application in telecommunications systems, in such areas as add-drop multiplexing of WDM channels and dispersion compensation. Apart from their excellent filtering characteristics, such applications benefit from the ready integration of fibre gratings to fibre systems, their low insertion loss and polarisation insensitive operation. Common apodised grating designs usually exhibit an almost flat spectral response with sharp cut-off edges. However, SSFBGs, which are a more sophisticated class of fibre gratings in terms of design and fabrication, allow for the implementation of filters with almost arbitrary spectral response, thereby enabling applications that require precise control over the temporal and spectral characteristics of optical waveforms.

Such an application is the encoding and decoding of short optical pulses. A temporal code can be imprinted on the spatial structure of a fibre Bragg grating by imposing a relatively slowly varying modulation envelope upon the rapidly varying refractive index modulation of the grating. This can be either a phase or an amplitude envelope, depending on whether the code is to be phase- or amplitude-shift keyed. We fabricate such gratings using a 'plane-by-plane' grating writing technique, which has the flexibility to allow the fabrication of complex SSFBG structures without relying on complex phase masks.

When a short pulse at a wavelength matching the Bragg wavelength of the SSFBG is reflected from the grating, it will be transformed into a waveform with a temporal

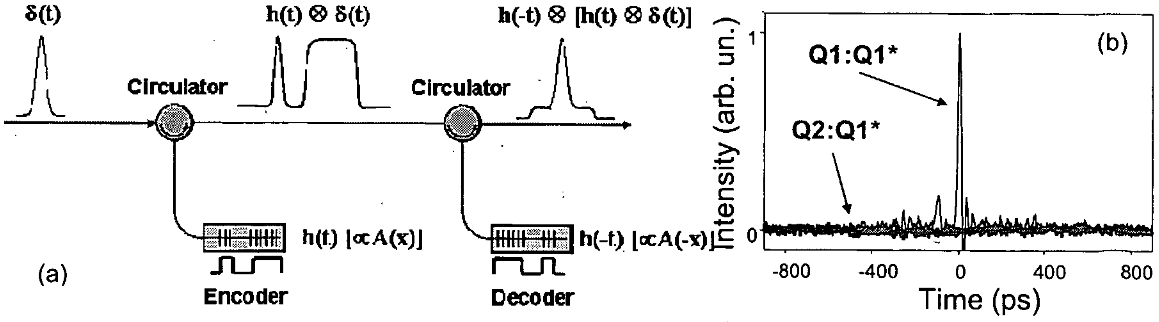

Figure 1: (a) Schematic representation of pulse encoding and decoding using SSFBGs; (b) Examples of the decoder output in the matched and unmatched cases for 255-chip quaternary phase coded SSFBGs.

shape that follows the shape of the code of the grating. Similarly, a temporal code can be 'read' using a second (decode) SSFBG. This SSFBG is required to have the same code imprinted on it, however it should be spatially inverted relative to the incoming code. This ensures that the decode SSFBG acts as a matched filter to the incoming code, and the reflected output is the autocorrelation of the code (Fig. 1). Incorrect codes will see the decoding SSFBG as a cross-correlator, and if the codes have been selected appropriately, this will result in a low intensity signal (Fig. 1b) [1, 2]. Thankfully, due to the popularity of CDMA schemes for wireless systems, several code families are available with excellent auto- and cross-correlation properties. In general, phase codes outperform amplitude codes, however they require coherent signals to be used throughout the system. Special care has to be taken then to ensure that coherent interference between different users will not be a major limiting factor to the system performance [3].

Nowadays it is possible to fabricate SSFBGs with code lengths longer than 256-chips, and a duration of less than 6 ps per chip. In an Optical Code Division Multiple Access (OCDMA) system, where the data pulses of each user are encoded before being transmitted, long code sequences ensure that more users can be accommodated within the system, whereas a short chip duration allows for higher data rates to be employed.

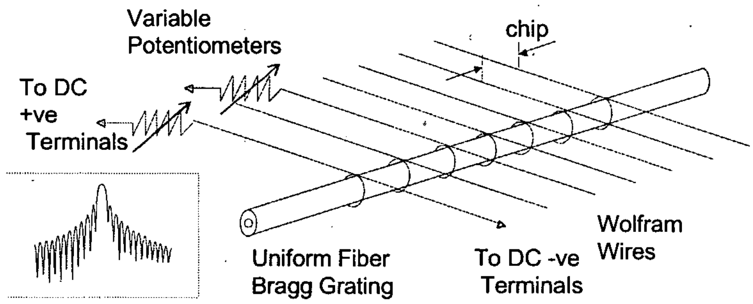

Figure 2: Reconfigurable fibre grating-based coding device. Inset shows the spectral response of the uniform fibre Bragg grating.

The codes written on SSFBGs are fixed, and although fibre gratings can be tuned in wavelength, if the address of the encoder or the decoder needs be changed, then the SSFBG normally has to be replaced. The arrangement shown in Fig. 2 overcomes this limitation in device functionality and system usage by enabling full reconfigurability for phase codes of a given chip duration and code length. Its operation is based on the observation that a discrete phase shift can be achieved in a fibre grating as a result of a change in the local propagation constant. This in turn, can either be caused by a variation in the grating period or the effective refractive index. Both these variations occur when the temperature of a fibre grating is elevated, with the thermo-optic effect being the dominant between the two [4]. In the arrangement of Fig. 2 a series of equally spaced tungsten wires (18 μm diameter) is laid across a uniform fibre Bragg grating. The wires are connected via variable potentiometers to an electrical current source to provide adjustable localised heating. Only modest current levels (typically <100mA) are required to induce a phase change of up to 2π. To date we have demonstrated devices that can accommodate up to 16 chips with a chip duration as short as 25 ps (corresponding to a wire separation of ~2.5 mm).

3. Characterisation of codes

Equally important to the generation of complicated encoded waveforms is the capability to accurately characterise and measure them. This is more so, when reconfigurable systems are considered, where a decoding device has to be tuned to a particular code. A suitable characterisation technique should have a fast response time and be capable of measuring both the intensity and the phase of short waveforms. A number of all-optical Frequency Resolved Optical Gating (FROG) techniques, including Second Harmonic Generation FROG (SHG-FROG), have been developed that allow the complete phase and amplitude characterisation of short optical pulses. Unfortunately these techniques use a nonlinear optical process to perform the required gating and thus are really only suitable for measuring relatively high peak power, short duration pulses. This restricts their suitability for telecommunication applications where the pulse durations of interest can be quite long, and the power levels involved are relatively modest. However, a new form of FROG technique has recently been developed in which a fast Electro Absorption Modulator (EAM) is used to perform 'linear' frequency resolved sampling [5]. This EAM-FROG technique offers many advantages over conventional FROG techniques including a far greater sensitivity, increased dynamic measurement range, low polarisation-sensitivity and applicability to much longer optical pulses. Moreover, EAM-FROG can be easily implemented using readily available telecommunication grade components and equipment [6].

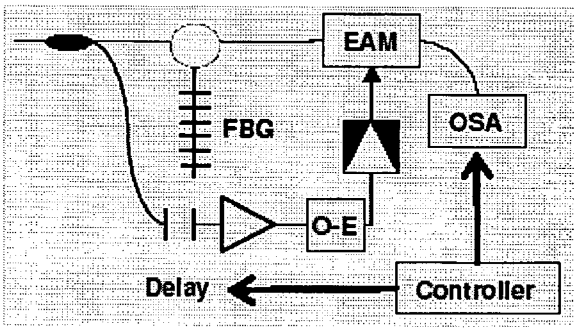

Figure 3: Experimental set-up for the characterisation of pulses shaped from an SSFBG.

Fig. 3 shows the schematic of our pulse-shaping/EAM-FROG characterisation setup [7]. The input pulse train comprising 20 ps pulses at a repetition rate of 1.25 GHz is first split using a 3 dB fibre coupler. The pulses from one arm of the coupler are reflected from the pulse-shaping grating under test. The shaped pulses are then input to the EAM. The synchronous pulse train from the second arm of the coupler is passed through a computer controlled optical delay stage before being detected by a fast (>33 GHz) optical detector to generate short electrical pulses at 1.25 GHz. These pulses are then amplified and low-pass filtered in order to generate a 1.25 GHz almost sinusoidal electrical drive signal to the EAM. This drive signal creates a short (~50 ps long) switching window that is synchronous with the shaped optical pulse train incident to the EAM. The shaped optical pulses are thus optically sampled by the EAM. By varying the optical delay in a controlled fashion and measuring the resulting spectrum on a high performance Optical Spectrum Analyser (0.01 nm resolution and >70 dB dynamic range), we build up a spectrogram of the shaped optical pulses.

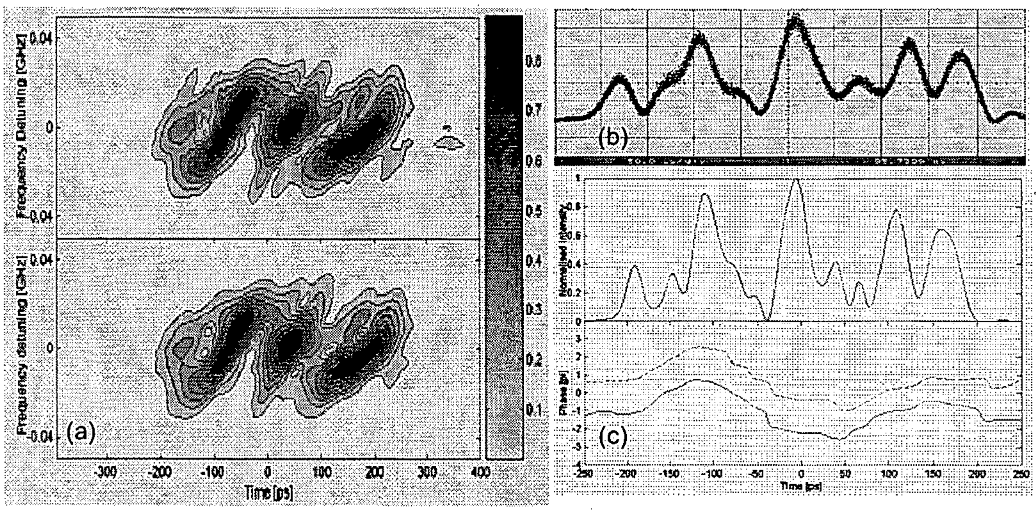

Figure 4: (a) Comparison between measured (top) and retrieved (bottom) spectrogram of pulses reflected off a 16-chip phase-shifted grating. (b) Direct oscilloscope trace measurement, and (c) retrieved intensity (top) and phase profile (bottom) of the same pulses.

We used this technique to characterise SSFBGs with 16, 4-level phase shifts in their structure and a 25 ps chip duration. Fig. 4a shows a typical measured and retrieved spectrogram of the 20 ps pulses reflected from the SSFBG. As can be seen excellent agreement between the retrieved and experimental spectrograms is obtained confirming the quality of the measurement processes. In Fig. 4b we show a direct oscilloscope measurement of the encoded waveform obtained with a 20 GHz bandwidth photodetector and in Fig. 4c we plot the temporal pulse characteristics (intensity and phase) as retrieved from the spectrogram of Fig. 4a. Considering the ringing effects and the limited resolution of the 20 GHz photodetector, there is good agreement between the two intensity plots. The theoretical prediction of the phase response for the idealised grating is superposed on Fig. 4c. All of the key features of the expected pulse shape are observed experimentally. However, it should be noted that the phase features are not as abrupt as would probably be expected, because the input pulses are only slightly shorter than the chip length. Note also that the temporal resolution of the measurement is not limited by the (~50 ps) temporal width of the EAM gating window and is sufficient to resolve the much faster rise time of the reflected pulses. This is due to the fact that in FROG both temporal and spectral data are used to determine the pulse shape as opposed to conventional optical sampling where the width of the sampling window ultimately defines the temporal resolution [8]. Equally good agreement between theory and experiment was obtained for various measurements on the reconfigurable coding devices.

4. System applications

The first experimental demonstration of an OCDMA transmitter and receiver based on SSFBG technology was reported in 1998 [9]. In these experiments 7 chip, unipolar codes were generated and decoded. Since then there have been numerous demonstrations of SSFBG-based OCDMA systems, making use of long, multi-polar codes and operating at Gbit/s data rates (see e.g. [1, 2, 10-12]). Perhaps the most significant feature of the SSFBGs OCDMA approach is that it is by its very nature fully compatible with conventional WDM techniques. This is demonstrated in

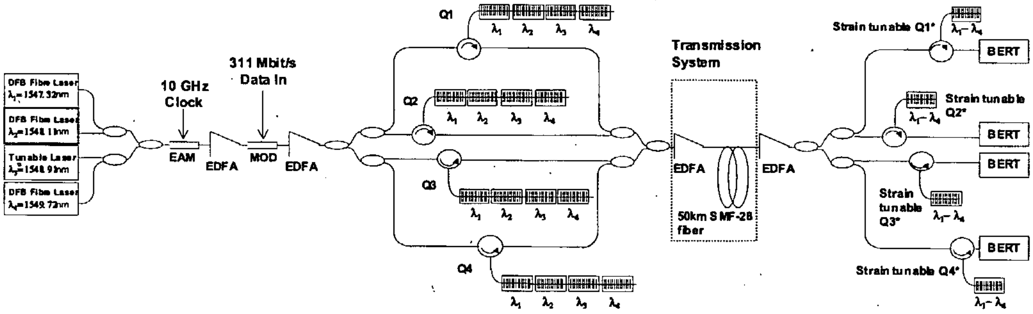

Figure 5: Experimental set-up of a 16-channel OCDMA/WDM system.

the system shown in Fig. 5 [11]. Four lasers, all separated in frequency by 100 GHz are used within the transmitter. The output from these lasers is first combined into a single fibre and then fed into an EAM. The EAM, with a chirp parameter, α=-0.5, is used to generate 10 GHz, 20 ps WDM pulse trains. The pulse trains are then amplified and modulated using a $LiNbO_3$ intensity modulator to obtain a 2^7-1 pseudorandom data sequence at 622 Mbit/s. The modulated pulses are then reflected from an array of 16 coding gratings (four different OCDM codes centred on four different wavelengths) to generate 16 simultaneous coded data channels. The four level phase shift keyed OCDM codes are derived from the Family A sequences and which provide for more desirable auto/cross-correlation characteristics than lower level coding schemes such as unipolar and bipolar code sequences [13]. The 16 different coding SSFBGs were fabricated to have a chip duration of 50 ps, resulting in a total grating length of 8.22 cm. All the 16 coded channels are combined together and transmitted over a distance of 50 km of standard single mode fiber having a total dispersion of ~812 ps/nm before being split and fed on to four decode gratings matched to the particular codes and wavelength channels. Hence all four different OCDM code channels located on the same wavelength can be decoded simultaneously and the performance of each individual channel can be evaluated by measuring the bit error rate (BER). Inset within Fig. 6a is the optical spectrum of the 16-channel OCDM/WDM signal incident to one of the decode gratings. The optical spectrum of the decoded response of grating Q1* to the combined 16-channel input is shown in Fig. 6a. Fig. 6b shows the eye diagrams obtained at a data rate of 311 Mbit/s without transmission and with 50 km of

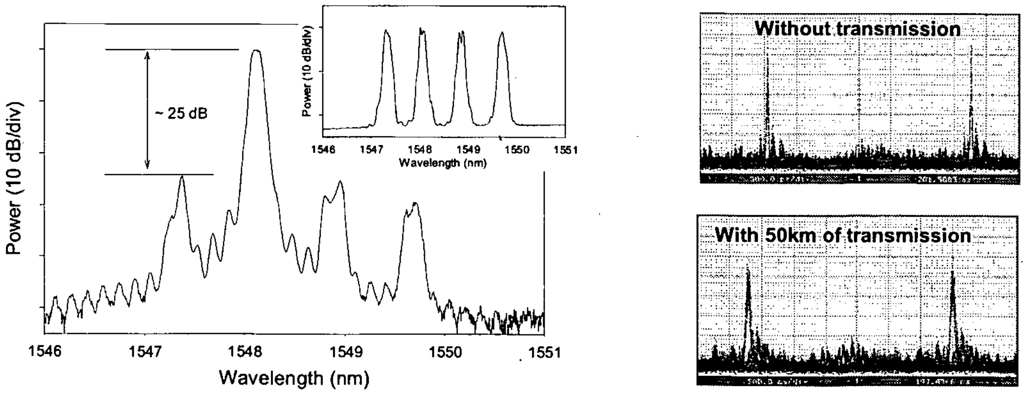

Figure 6: (a) Spectrum of one channel after decoding (Inset: spectrum of the transmitted signal); (b) eye diagrams after decoding without transmission (top) and after transmission over 50 km of SMF.

standard fibre inserted between coding and decoding respectively. Clean eyes are observed confirming that good code recognition quality is obtained despite the presence of the other 15 interfering channels. These plots show that using just a single decode SSFBG we can simultaneously perform both the wavelength 'drop' function (with ~25 dB of extinction between adjacent wavelength channels), and the channel decode function in the time domain.

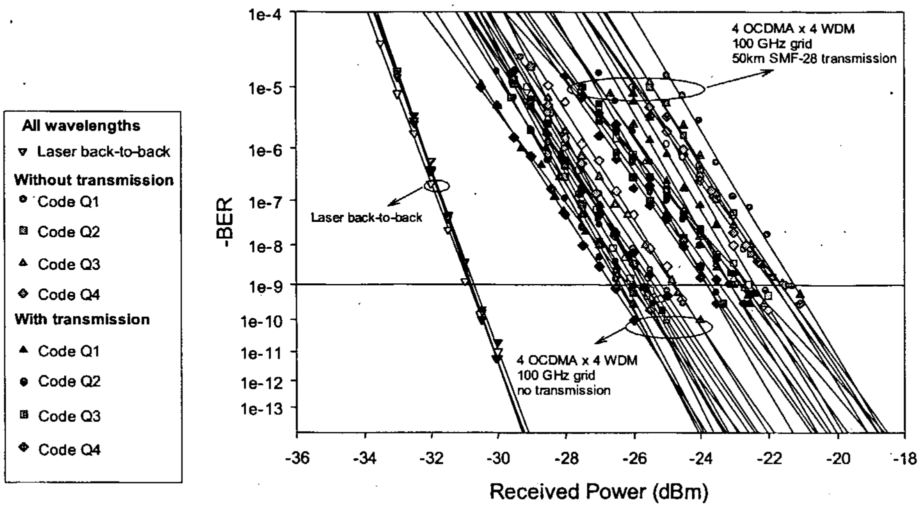

Figure 7: BER measurements for the 16 channels of the system of Fig. 5 with and without transmission.

In Fig. 7 we plot the BER measurements against the total received optical power for each channel in the presence of the other 15 interfering channels. Error free performance is obtained for all the 16 channels without transmission over 50 km of standard fibre. Note that a large proportion of the apparent ~5 dB power penalty compared to the laser back-to-back case results simply from the increased incident average power due to the additional 4 in band OCDMA channels. A further ~2 dB of power penalty is observed for all the channels when the 50km of standard fibre is inserted between the code:decode process. However, we are still able to obtain error free operation in this case without any requirement for dispersion compensation; certainly this penalty can be reduced with the incorporation of dispersion compensating elements, albeit with an increase in system complexity. Note also that this is a purely linear system. If we were to introduce some form of nonlinear thresholding at the receiver we should anticipate a significant improvement in both system performance and capacity both in terms of number of simultaneous users per wavelength, and data rate per OCDMA channel [14, 15]. Again though there is a cost in terms of system complexity and practicality.

5. Conclusions

In this paper we have elaborated on several aspects of pulse encoding/decoding technology using SSFBGs. We have described the basic principles of operation of these devices and shown how we can achieve reconfigurable operation with a device that uses a single uniform fibre Bragg grating. We have also shown detailed characterisation results of pulses shaped by encoding SSFBGs, and described a hybrid 16-channel OCDMA/WDM system. OCDMA may prove to be a useful alternative to WDM in future high capacity access networks requiring high granularity and flexible bandwidth allocation. However, the concepts of pulse encoding and decoding can also be extended and applied to other network schemes, such as bit-serial optical packet switching [16]. Moreover, these applications promise an even better performance, since they can make use of the excellent matched filtering characteristics of the decode devices without having to cope with multiple-access interference.

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