Security System for Optical Communication Signals With Fiber Bragg Gratings

P. Torres, L. C. G. Valente, and M. C. R. Carvalho

***Abstract*—A security system for optical communication signals based on Bragg grating structures is presented in this paper. The technique can be implemented in different levels of sophistication with corresponding cost and technical difficulty. The technique is demonstrated in its simplest version with an array of two fiber Bragg gratings in each side of the optical link. The principle has been tested with a periodic pulse train of 1.4-GHz repetition rate. A simulation that allows the design of more sophisticated systems is also presented and show very good agreement with experimental results.**

***Index Terms*—CDMA, fiber Bragg grating, optical encryption, security system.**

I. Introduction

The development of techniques for writing fiber Bragg gratings has opened new possibilities in optical communications applications. Fiber Bragg gratings have been implemented in a variety of optical signal processing devices, such as add/drop multiplexers for wave division multiplexing (WDM) [1] to augment the carrying capacity of optical-fiber networks, mode converters [2], dispersion compensation [3], [4], and pulse compressors [5]. Recently, there has been tremendous interest in applying multiple Bragg grating structures to decompose a broad-band pulse simultaneously in wavelength and time [6]. When a broad-band light pulse reaches a series of different Bragg gratings, each part of the spectrum will be reflected at different position. Depending on spectral characteristics of the source and gratings, and on the spacing between gratings, the pulse may be broadened or even spit into a number of separated pulses. One immediate and important application of this spectral decomposition is in the codification of pulses to implement optical CDMA [7]–[10] systems. As the receiver necessarily uses an inverted grating structure to decode the transmitted signal, it is important to know the complete response of the original multiple granting in order to fabricate the correct complementary one. This task is not easy because the ultrashort pulses are deformed by a single grating [11]. As a consequence, the decoded pulses have longer temporal duration [9]. Therefore, dispersion is a limitation to optical CDMA systems.

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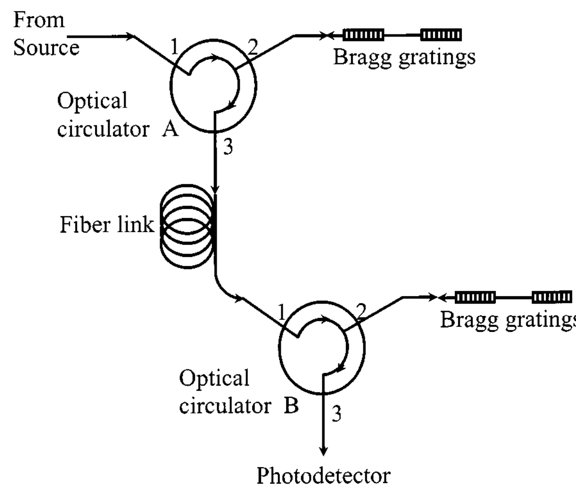

Fig. 1. Experimental setup used to encrypt and decrypt the optical signals.

As an extension of the CDMA system, in this paper, we propose a technique for scrambling optical communications signal. As discussed, it can be implemented in levels of complexity, resulting in more or less security and with the corresponding technical difficulty of installation and operation. The simplest version has been experimentally demonstrated and is shown to be compatible with bit rates up to 10 Gb/s.

II. Fundamental Scheme

If a broad-band (continuous or multiple discrete wavelength) source is used to generate optical communication pulses, these pulses can be arbitrarily spread in time by using an array of Bragg gratings in a configuration like the one presented in the experimental setup of Fig. 1. As light will travel two times the space inside the grating array, each centimeter will impose 100-ps delay; considering high bit rate systems, it is easy to introduce delays much longer than the bit period. It should be clear that as each pulse will be split into a series of lower power pulses, the transmitted information will not be recognized at the receiver, unless the pulses are packed back together using an inverted sequence of Bragg gratings.

This simple approach can be considered as a way of encoding the information results presented in Section III, clearly demonstrate the possibility of implementation with pulses comparable with those of an optical 10-Gb/s communication system. Up to this point, an unauthorized recipient could simply use a spectral filter to select only light coming from one of the Bragg

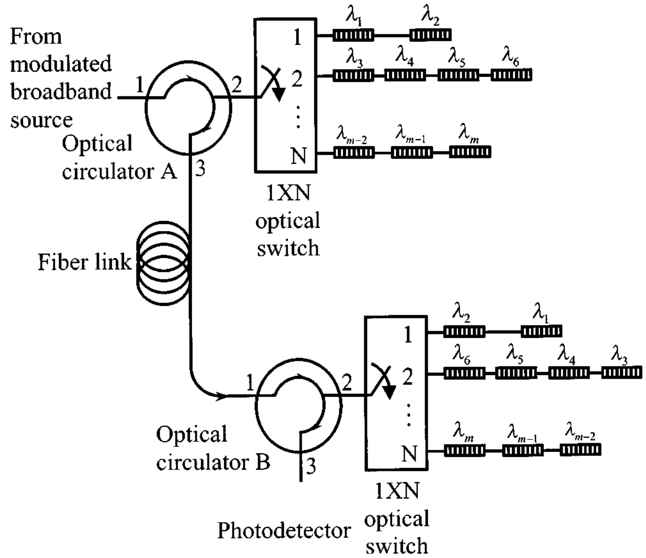

Fig. 2. Schematic configuration of the proposed system for encrypt/decrypt optical communication signal.

gratings, and as each wavelength contain all the information, it would not need to use light from other Bragg gratings. Even though there is still to be considered the power needed for a good signal-to-noise ratio at the receiver, this would be a fragile way of encryption. The signal-to-noise ratio will be reduced as $1/N$, where N is the number of gratings.

III. Other Implementations

If, instead of the previous situation, each wavelength has only part of the transmitted information, this will force the recipient to read the bits coming from all Bragg gratings and to compensate for the relative delays imposed by the transmitter grating array in order to recover all the information. There are different ways of achieving this situation; we present here a short discussion of three of these possibilities.

The first one is to randomly vary the spectrum of the source in this way, although the grating array has fixed spectrum and delays, each grating will only reflect light during part of the total transmission time. An unstable multimode Fabry–Perot laser, one or more temperature-tuned distributed feedback (DFB) lasers or the amplified stimulated emission (ASE) from an erbium doped fiber amplifier (EDFA) passed through a time-dependent filter are good candidate sources for this implementation.

A second possibility is to have more than one grating array at the transmitter end. These arrays must be part of a longer array that will be used by the authorized recipient. The transmitter uses a $1 \times N$ fiber switch to randomly change from one sub array to another.

The third implementation, schematically shown in Fig. 2, uses totally different arrays at the transmitter side and the recipient has the same collection of arrays. This would probably be the most secure scheme, but will certainly reduce the transmission speed, as it demands switching time from one array to another, as well as some kind of synchronization.

These possibilities can be mixed, leading to even more complex ways of codification and could also be implemented with tunable Bragg gratings allowing fast reconfiguration of the setup. Finally, one could separate part of the spectrum to be modulated and the rest to be send as continuous wave (CW) light, which will avoid the identification of the spectrum of the gratings used and will create a continuous background level, making it even more difficult the task of breaking the code.

IV. Experimental Results

Different criteria can be used to design the Bragg grating sequences. In this paper, we work with the simplest possible version, with only two gratings in each side of the optical link in order to gain physical insight into the dynamics for encrypting optical signal. This will also provide insight into the design of more complex grating structures

The gratings were written, using an interferometric setup, the writing beam is the fourth harmonic Nd : YAG laser light at 266 nm with Q-switched mode-locked 100-ps pulse duration [12]. The resulting gratings had Bragg wavelength of 1548 and 1560 nm, the full-width at half maximum (FWHM) were of approximately 2.5 nm, the peak reflectivity was near 50%, and their length was 0.5 mm. The ASE light from a commercial EDFA (HP2001) was used as the broad-band light source that was externally modulated by an electrooptic modulator (GEC Y35–8808-02). As can be seen in Fig. 2, after being polarized and passed through a polarization controller, this signal goes into port 1 of the optical circulator A and is sent to port 2, where it will be encrypted by two Bragg gratings; the reflected part comes back and goes to port 3, where it is transmitted by a fiber link. At this point, the signal should not be recognized without the aid of the decoding gratings. To recover the signal, a similar configuration, with the gratings in inverted order, is connected to circulator B before going to the photodetector. The distance between gratings was 3.5 cm, which imposes a round trip delay close to 350 ps.

A. Two-Grating Operation

To check the delay and capability of recovering the original signal, the system was operated with short pulses of 100 ps at a repetition rate of 1 GHz. Fig. 3 shows the optical signal at three different points of the optical circuit measured with detection system with a response time of 40 ps. From top to bottom, we see the original signal, the output from circulator A, and the output from circulator B. It is clear that each pulse is duplicated with no noticeable distortion by the first two gratings and that the time separation is 352 ps, which is very close to the expected value.

To demonstrate the operation of the system in a situation closer to a real data transmission, we used a periodic signal of 1.4 GHz with a duty cycle close to 50%. This signal is equivalent to sequence of ones and zeros in a system operating at 2.8-Gb/s nonreturn to zero (NRZ). The results presented in Fig. 4(a)–(c) were measured at the input of circulator A, A (encrypted signal), and at the output of circulator B (decrypted signal), respectively. The encrypted signal is completely different than the input, where the basic frequency has been totally canceled and

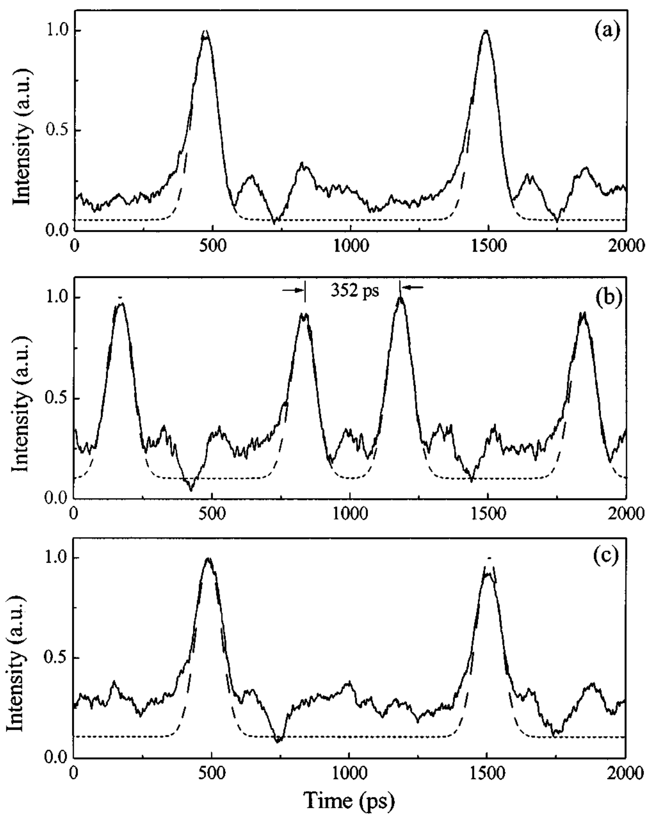

Fig. 3. Results for a periodic pulse train at ~1.4 GHz. (a) Input. (b) Encrypted. (c) Decrypted. The dashed lines are the simulated signals using the shape fitted of the input pulse.

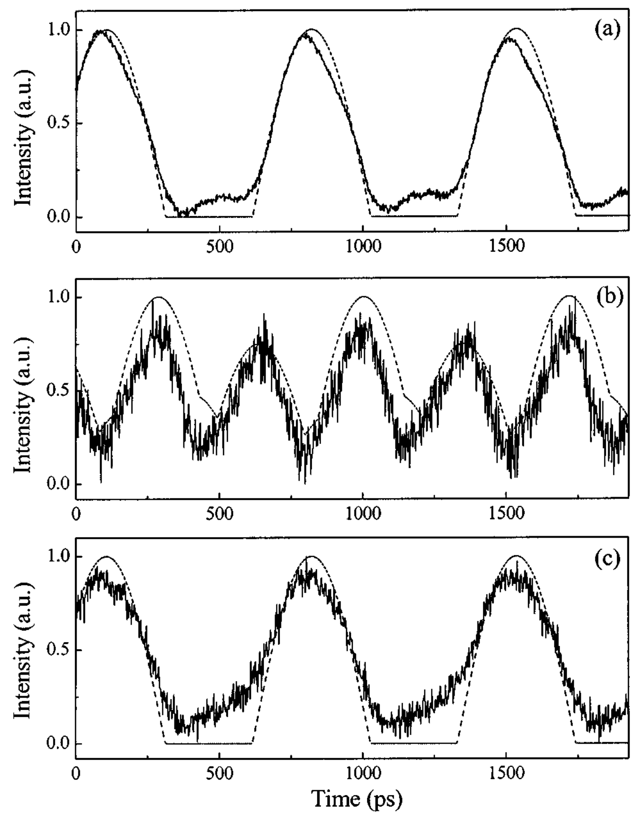

Fig. 4. Results for an equivalent signal of a system operating at 2.8-Gb/s NRZ. (a) Input. (b) Encrypted. (c) Decrypted. The dashed lines are the simulated signals using the shape fitted of the input pulse.

only a small second harmonic signal is present. At the output of the decoder, the signal is recovered with very good fidelity. In the demonstration presented here, the total loss of the encrypting and decrypting system was estimated to be of 29 dB, which include losses in the circulator (~6 dB) nonideal reflectivity of gratings (~6 dB) and reduced total spectral width of gratings (~10 dB). The fiber link was smaller than 1 km and its loss was not considered in this evaluation. Depending on the spectral characteristic of the source and on the number of gratings, these losses can be significantly reduced.

B. Numerical Simulation

In both Figs. 3 and 4, experimental results are presented with the prediction obtained from a simulation under the consideration that each grating imposes no temporal distortion to the pulse. The basis for this consideration is that the pulse in the fiber has a physical length larger than the grating length; in such a case, any temporal fraction of the pulse interacts with the grating during a time shorter than the duration of the pulse, thus the reflected pulses have approximately the same temporal shape and duration of the input pulse. Both encrypted and decrypted signals are simulated using the shape fitted to the input pulse. The amplitude of each reflection was taken from the experimental results shown in Fig. 3. Using this software, it is possible to design more sophisticated systems and check their performance at different bit rates. It is also possible to investigate the operation in multiplexed systems.

V. Discussion

Although in its simplest possible version, with only two gratings on each side of the optical link, this setup has proven to be applicable to practical communications systems. Considering the duration of the pulse and the excellent correlation of the recovered signal with the original one, as can be seen in Fig. 4, it can be stated that this setup can be used in systems operating with NRZ codes up, at least, 10 Gb/s. Fig. 4(b) give an idea of case that the decoder has the appropriated wavelengths, but wrong delay; in this condition, it is equivalent to have a zero relative delay. It is important to point out that the ultimate frequency limitation of this technique is the length of each individual grating, which must be shorter than the half-length of the pulse. For typical gratings of 1 mm, this represents pulses of 20 ps. Besides the different possible ways of temporally changing the transmitted spectrum and consequently forcing the recipient to have the complete decoding array as previously discussed, some practical details should be pointed out. The use of a larger number of gratings is recommended for two main reasons: first, the complexity of the encryption, which increases the security of the system, and second, the power at receiver, which will be closer to the available power from the broad-band source. In the case of long distances, where the fiber dispersion may have an important contribution in the separation of different wavelength pulses, the decoding structure will not be exactly the same as the encoding one, as it must also compensate for the fiber dispersion. For digital systems, the distance between gratings has to be such that the differential delay imposed by the encoding structure is, at least, on the order of a bit slot.

VI. Conclusions

In summary, in this paper, we have proposed a technique to scramble optical communications signal by using fiber Bragg gratings. The principle was demonstrated with the simplest version of two grating in each of the fiber link, showing good results to signal of up to tens of gigabits per second. A numerical simulation has been developed and allows the evaluation of the operation with complex grating arrays. Also been discussed have been some possible alternatives in order to increase the security of the system by continuously changing the transmitted spectrum and/or the transmitted code.

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