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Reconfigurable All-Optical Header Recognition for Packet Switched Networks

C. Tian, Z. Zhang, M.A.F. Roelens, M. Ibsen, P. Petropoulos, D.J. Richardson

Abstract — **We report on an optical packet switching system with a code-reconfigurable switching node. Packet headers are generated and decoded in an all-optical fashion using fiber Bragg gratings (FBGs). The reconfigurable 15-chip, 25 ps/chip quaternary phase coding decoder is based on a uniform FBG, the code of which can be changed dynamically by thermally inducing appropriate phase shifts. We present characterization results on the code-reconfigurable FBG device as well as performance evaluation of the switching system.**

Index Terms—**optical packet switching (OPS), fiber Bragg grating (FBG)**

I. Introduction

Optical packet switching is a promising technology for future all-optical networks. Optical packet switching can direct packets through an optical network without the need to pass the packets through electronics. It thus has the advantage of overcoming the bottleneck associated with electronic processing, providing higher bandwidth utilization and payload transparency. The main processing functions of packet switched networks are associated with the header of the packets. The capability to generate and reliably "read" the header information is of fundamental importance, since this function is responsible for the generation of the control signal which determines how the packets are routed.

Several schemes for tagging the optical header to the data payload have been proposed and demonstrated. In general, the header can either be allocated in different spectral regions, in which header and payload are overlapping in the time domain, or it can be allocated serially in time with the payload, as in the normal implementation of an electrical router. In the first case, there is no strict timing or synchronization requirement at the bit level between the label and the payload, while the latter case is more spectrally efficient and the interference between the header and payload can be kept at a minimum level.

The multiwavelength labeling scheme [1, 2] employs separate wavelength channels for the payload and header. Header extraction and processing is simple but the spectral efficiency of the scheme is low. Moreover, different wavelengths have different phase velocities when propagating in a dispersive fiber, resulting in a walk off between the header and the payload.

Both the header and the data payload can be accommodated on the same optical wavelength with optical subcarrier multiplexing (SCM), by treating the payload as a baseband signal and modulating the header on the subcarrier [3] [4]. However, some crosstalk between the header and payload is unavoidable. It also places stringent requirements on the modulator and the receiver. Orthogonal modulation [5] is another labeling technique, in which differential phase shift keying (DPSK) or frequency shift keying (FSK) labels are modulated on the intensity modulated (IM) payload. However, the extinction ratio of the header and payload has to be compromised to ensure they can be separated efficiently.

There are various bit-serial time-domain labeling techniques. The main challenges facing these systems are how to discriminate the header from the packet, as well as how to process the information included in the header, which in this case has to be a fast waveform, in order to ensure that efficiency is not compromised. Both Refs. [6]and [7] relied on the application of different types of modulation for the header and the payload, and subsequently used nonlinear effects in a semiconductor optical amplifier to discriminate one type of data from the other.

We have previously studied extensively the feasibility of optical coding/decoding using super-structured fiber Bragg gratings (SSFBGs) as matched filters[8]. Whereas these concepts have been directly applied for the all-optical implementation of OCDMA systems, they can also offer the unique potential to perform all the required processing for the labels of packet switched systems in an all-optical and linear fashion. Fig. 1 shows the principle of packet generation and header recognition using SSFBGs [9]. The packet header is a specific sequence of individual pulses (a code), generated from the reflection of an input pulse from a single encoding SSFBG. The code is written on the SSFBG by means of a spatial amplitude or phase envelope superimposed upon the otherwise uniform FBG refractive index modulation. Header recognition is performed by a second (decoding) SSFBG, which has the time-reversed profile of the encoding grating. A strong autocorrelation peak appears when the header is injected into the corresponding decoding SSFBG, while low intensity noise-like cross-correlation appears both for the payload and headers that do not match the decoder. The autocorrelation peak can be easily detected using threshold

Manuscript received June 27, 2005. The authors are with Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK (phone: +44 2380 593136, fax: +44 2380 593142, e-mail: cht@orc.soton.ac.uk)

detection and used to control the routing.

Compared to other bit-serial labeling techniques, SSFBG-based all optical header generation and recognition offers the additional advantages of all-fiber low cost operation, passive generation of the codes with the capability to accommodate large address spaces (511-chip OCDMA codes have been demonstrated [10]). All header processing is performed optically and at one step. In addition, there is no restriction on the modulation format used for the payload, making the system totally transparent. However, from a systems point of view, a dynamic header recognition function, i.e. the capability to program the decoder to "read" different labels, is highly desirable in an optical switching node to maximize the network flexibility.

In this paper we investigate the feasibility of code-reconfigurable header generation/recognition based on FBGs. We describe the operation and performance of our device, and present some preliminary tests of a reconfigurable all-optical packet switched system.

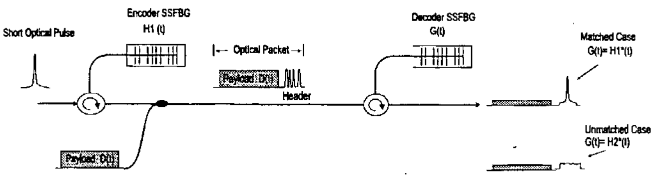

Fig. 1 Principle of optical header generation and recognition using SSFBGs.

II. CODE-RECONFIGURABLE DEVICE

A. Description

When a uniform FBG is locally heated by a fine electrical heater, which elevates the local temperature of the grating, a phase shift occurs at the heating point due to the change in the effective refractive index (thermo-optic effect). By tuning the current flowing through a fine electrical heater, the magnitude of the induced phase shift can be controlled.

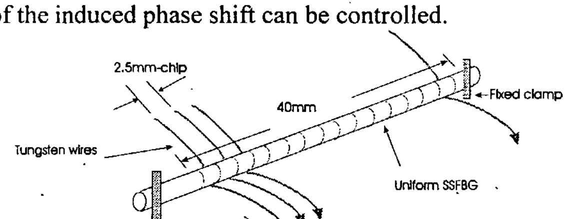

Fig. 2 Structure of a 15-chip code-reconfigurable device based on a uniform FBG.

Fig. 2 illustrates the structure of a 15-chip code-reconfigurable device based on a uniform FBG, with a peak reflectivity of ~60%. The 40 mm long grating is mounted on a fiber stretcher to allow tuning of the grating Bragg wavelength. 15 parallel tungsten wires with an 18 μm diameter are laid under the FBG. The tungsten wires are placed 2.5 mm away from each other. This distance determines the spatial length of the code chips and corresponds to a chip duration of 25 ps. The current flowing through each tungsten wire is controlled independently to produce the desired code. A temperature control device is applied on top of the grating to compensate for environmental temperature fluctuations.

B. Characterization

By performing the standard FBG characterization procedures, i.e. by measuring the reflectivity spectra and time delay response as a function of wavelength, one can only obtain limited and indirect information on the phase distribution along the grating. Moreover, there are many parameters which can affect the reflectivity spectra making it both tedious and difficult to obtain reliable results, especially when thermally induced phase shifts are present, which have some kind of spatial distribution along the grating.

We used a new method, EAM-FROG [11], to directly measure and calibrate the phase response of the grating. Fig. 3 shows the schematic of the characterization set-up. Short laser pulses are split into two paths. The pulses in one path are reflected from the grating under test, and then fed to the electro-absorption modulator (EAM). The pulses in the other path pass through a computer controlled optical delay stage before being detected by a fast optical detector to generate a short electrical pulse, which is used as the driving signal to the EAM. The shaped optical pulses are thus optically sampled in the EAM by the synchronous electrical gate pulses. By varying the optical delay in a controlled fashion and measuring the resulting spectrum on a high performance optical spectrum analyzer, we obtain a spectrogram, from which we can retrieve the full (intensity and phase) information on the reflected pulse from the grating. Compared with conventional FROG techniques, EAM-FROG has several advantages including a far greater sensitivity, increased dynamic measurement range, low polarization sensitivity and applicability to measure much longer optical waveforms. We have already verified the capability and accuracy of EAM-FROG by using it to characterize both single phase shift and 15-chip discrete (fixed) quaternary phase coded SSFBGs[12].

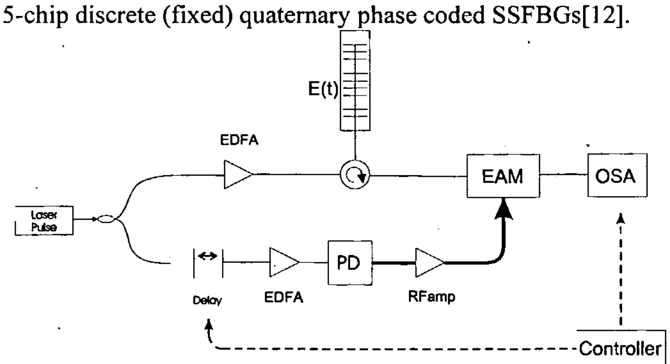

Fig. 3 The basic schematic of the EAM-FROG set-up.

We used EAM-FROG in order to tune the operation of our reconfigurable coding FBG device. The normal phase levels of a quaternary phase code system are 0, 0.5π, π, 1.5π. To determine the electrical current value that induces the right phase shift to the FBG, we investigated the simple case of a 17 mm long uniform FBG with a single tungsten wire across its centre. 5 GHz 25 ps EAM-carved pulses were used at the input of the system. The pulses reflected off the FBG had a duration of ~170 ps. Fig. 4 (a-c) shows the retrieved results for heating currents of 52mA, 70mA and 84mA, which yielded phase shifts of 0.55π, 0.96π and 1.45π respectively. The retrieved pulse intensity profiles were in excellent agreement with independently measured oscilloscope traces. Fig. 4(d) shows the derived spatial phase distribution along the grating for different values of electrical current. The figure shows that the phase shifts are not actually discrete, but they extend to more than 3 mm in the FBG.

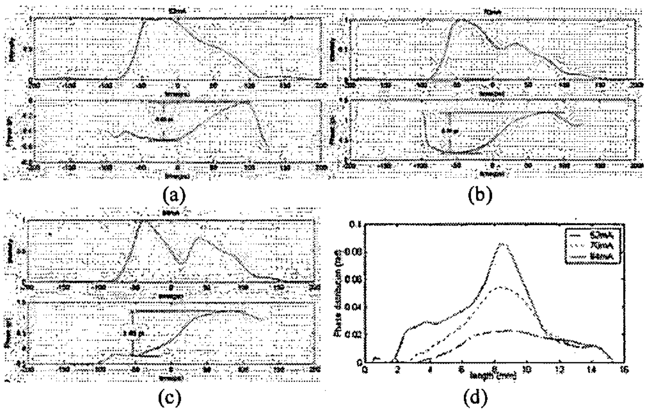

Fig. 4 Characterization results for the single phase shift tunable grating device

We used these current values to program the 15-chip reconfigurable FBG device and examine its decoding capability by using it in conjunction with a fixed 15-chip quaternary phase encoding SSFBGs (as shown in Fig.1). The codes of these SSFBGs were chosen from Code Family A which has been designed for 4-level phase coded systems [13]. For all the codes that we examined we obtained well-defined autocorrelation peaks (Fig.5a), and confirmed that low intensity cross-correlation signals were obtained for the unmatched cases (Fig.5b). Note that the chip length was actually shorter than the space occupied by the phase distribution in the reconfigurable FBG device, which highlights the robustness of the proposed matched filtering technique. In the following Section we demonstrate the use of these decoded signals to control the routers in an optical packet switched system.

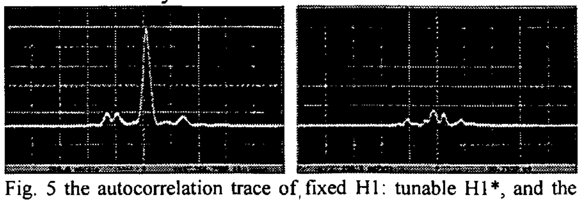
Fig. 5 the autocorrelation trace of fixed H1: tunable H1*, and the cross-correlation trace of fixed H1: tunable H2* (for fixed signal power).

III. PACKET SWITCHING SYSTEM

We set up a simple packet switching system, which incorporates a packet transmitter and a packet switching node. In order to simplify the set-up of this preliminary experiment, we have generated two types of packets. One was a 'full' packet with the optically coded header preceding the payload, whereas the other contained only the payload without any header attached to it. At the packet switching node, the header of the 'full' packet was decoded using the reconfigurable FBG, and the payload was dropped off accordingly.

A. Packet transmitter

The packet transmitter generated the payload and header and coupled them together to compose the labeled optical packets. Fig.6 shows a schematic of the packet transmitter and an oscilloscope trace of the generated packets. For this particular experiment we chose a packet length of 6.4 ns (i.e. 156M packets per second), which comprised a 5.2 ns payload, a 400 ps header, and 400 ps guard bands before and after the header. The 'full' packet and the packet without a header appeared alternatively.

A CW source tuned at the wavelength of the encoding SSFBG generated light which was first split using a 70:30 fiber coupler. 70% of the light was EAM-carved into a 10 GHz pulse train and then gated down to 78 MHz using a $LiNbO_3$ modulator. The generated 20 ps pulses were then reflected from a 15-chip 25 ps fixed quaternary phase coding SSFBG to generate the 400 ps long header. Light on the other arm of the coupler was intensity modulated a single $LiNbO_3$ modulator which generated the payloads for both types of packet. The pattern used to drive the modulator was clocked at 10 GHz and was 128 bits long, with the 1-12 and 65-76 bits set as '0' to accommodate the header and guard bands. The relative delay between the signals in the two arms was adjusted before they were combined together by a 3dB coupler, so as to position the 400 ps header at the center of its allocated slot.

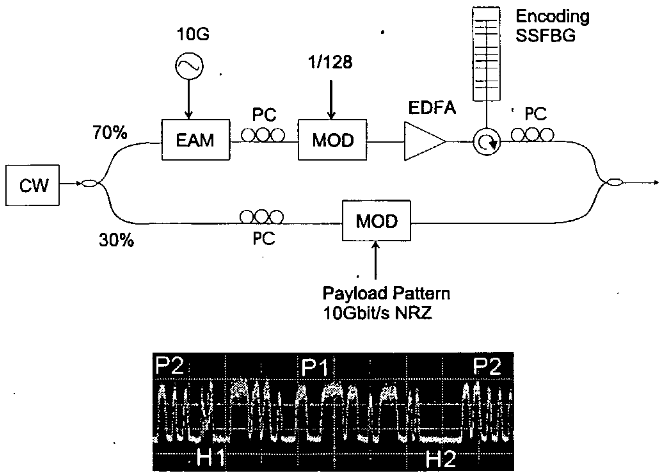

Fig. 6 Schematic of the packet transmitter and the generated packets

B. Packet switching node

At the packet switching node, optical header recognition was performed to control switching of the payload. Fig.7 shows a schematic of the switching node. The incoming packet stream was split by a 3dB fiber coupler. One part of the signal was input to a $LiNbO_3$ modulator which acted as an optical switch. The other part of the signal was injected into the 15-chip 25 ps code-reconfigurable FBG. The device was programmed to match the code of the SSFBG header generator. The resulting autocorrelation peak was detected by a photodetector and triggered an electrical pulse generator, which generated an electrical window to drive the $LiNbO_3$ switch.

Fig.7 also shows the reflected output of the decoding FBG device as well as the dropped payload P1. We have tested the system using two distinct coding gratings (H1 and H2), and have confirmed its correct operation by observing the signal before and after the switch.

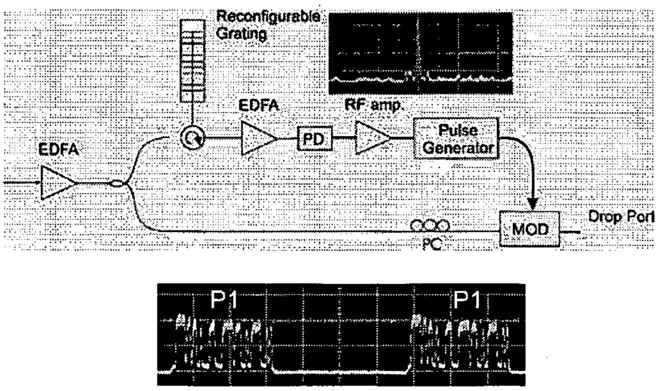

Fig. 7 shows the schematic of the switching node

We next measured the BER performance of header recognition using fixed H1: tunable H1* and fixed H2: tunable H2* respectively. Fig. 8 shows the BER results for the header recognition for the cases of without and with the data payload. An additional power penalty of ~3 dB is observed when the payload is transmitted alongside the header, which is purely because of the extra power reaching the receiver.

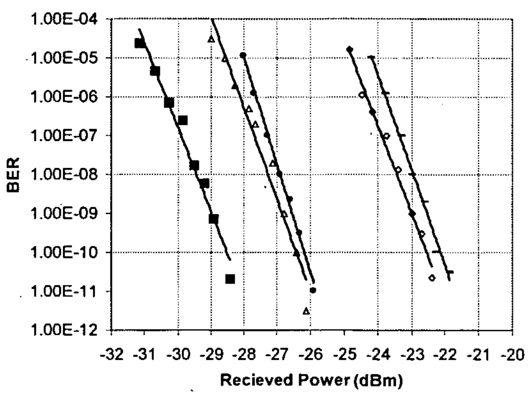

Fig. 8 BER performance for the reconfigurable header recognition. ■ Back to back, Δ H1:H1* without payload, ● H2:H2* without payload, ◊ H1:H1* with payload, - H1:H1* with payload.

IV. Conclusion

We have demonstrated a 15-chip 25ps quaternary phase code-reconfigurable header recognizer based on a uniform FBG. An optical packet switching system that uses SSFBGs to generate the header and the reconfigurable FBG device to recognize the header has been proposed and experimentally demonstrated. We are currently completing our experiments to include data with more than one labeling codes. Nevertheless, these initial results highlight the potential of the code-reconfigurable device for all-optical header processing in the optical packet switching applications.

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