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Multi-wavelength (40 WDM x 10 Gbit/s) optical packet router based on superstructure fibre Bragg gratings

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Summary
We demonstrate a multi-wavelength (40 WDM x 10 Gbit/s) optical packet router capable of processing 4 Gigapackets/s based on all-optical label generation and recognition using 16-bit, 20 Gbit/s four-level phase coding superstructure fibre Bragg gratings. Error free operation is obtained for the switched packets when all 40 channels are transmitting simultaneously.

Key words:
All optical label generation and recognition, superstructure fibre Bragg gratings, multi-wavelength optical packet router, matched filtering.

1. Introduction

There is an increasing need for high-speed optical networks that have a reconfigurable optical layer to provide a high-bandwidth, flexible core that is able to handle the bursty nature of internet protocol (IP) traffic whilst providing the quality of service required for voice and high definition video. Furthermore, the convergence of IP transport onto the optical layer will simplify the network architecture and protocols, effectively reducing the latency time associated with the electronic processing at the router. These networks are also required to support packet routing and forwarding functions operating at bit rates in excess of Tb/s that are compatible with current wavelength division multiplexed (WDM) transmission and routing.

Optical packet switching based on label routing is one such reconfigurable transport technology that is well matched to the bursty nature of IP packets and is completely transparent to the data bit-rate and format, enabling the efficient utilisation of the available fibre bandwidth. This technology is also compatible with the newly introduced IP routing protocols such as multi-protocol label swapping (MPLS) [1] by directly implementing the packet-by-packet routing and forwarding functions of MPLS in the optical domain. All optical packet switching, based on label routing, utilises an optical label, containing routing information, which is multiplexed together with the IP data packet. The generation and recognition of the optical label in these systems is carried out in the optical domain, which dramatically reduces the electronic processing requirements within the routing nodes.

A variety of all-optical coding schemes for packet labelling have been demonstrated, these include subcarrier modulation (SCM) [2], continuous-wave tagging [3], optical correlators based on planar lightwave circuits (PLCs) [4] and arrays of fiber gratings [5]. More recently, fibre Bragg grating technology has progressed to the point that the optical phase of light reflected from 'individual' gratings can also be exploited, allowing the use of optical phase as a coding parameter. Use of phase coding is significant since it is well known that bipolar codes exhibit far better cross-correlation/cross-talk characteristics than amplitude only unipolar codes. Phase encoded optical labels have been demonstrated using PLC, but this technique is limited by the maximum practical code length that can be readily achieved. The technique used to fabricate the fibre Bragg gratings is able to produce essentially continuous amplitude and phase control along an individual grating structure [6]. This particular technique is attractive in that it is far more flexible from a fabrication perspective than other techniques so far demonstrated and therefore allows for a far broader range of codes, and potential coding schemes. Most significantly it is not bounded by the current resolution limits and device lengths imposed by phase mask technology and offers great scope for the production of low cost optical label processing devices. Previously we have proposed and demonstrated the first all-optical packet switching technology based on all-optical label generation/recognition using phase-coded superstructured fibre Bragg gratings and switching using electro-optic modulators [7].

In this letter we demonstrate a 400 Gbit/s multi-wavelength (40 WDM x 10 Gbit/s) optical packet switched network node based on all-optical label generation and recognition using 16-chip quaternary phase-coded superstructured fibre Bragg gratings (SSFBGs), and switching using fast electro-optic switches. The routing look-up table is implemented in parallel all optically, using an array of SSFBGs label processors. All-optical label processing is completed in 1.6 ns, allowing packet processing rates of up to 4 Giga-packets per second (4 Gpps) within the node.

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Our routing approach is fully compatible with existing DWDM technologies and networks and, since both label and payload utilise the same wavelength, it is spectrally more efficient than techniques that place label and payload on separate wavelengths [8].

2. Principle of Operation

In the WDM based optical packet switched network each WDM channel carries data within optically labelled packets that can be independently routed through the network by packet switching nodes. The optical packet structure, shown in Figure 1, consists of an optically coded label followed by the data payload, both of which are on the same wavelength. The optical label contains the packet routing information that is used to control the routing of the optical packet within the optical packet switching nodes in the network. The coded label details the desired switch output for the packet it is associated with. Thus for a simple 2x2 packet router the routing information would specify whether the incoming packet was to be routed to either output 1 or 2 of the packet switch. The label and the data payload as well as the adjacent packets are separated by a small temporal delay (guard band). These guard bands are required to allow for the finite transition time of the optical space switch.

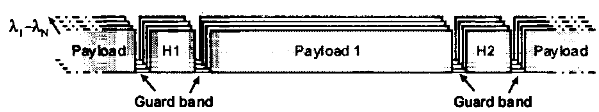

Fig. 1 Optical packet structure.

The functionality of the multi-wavelength optically packet switched node is illustrated in Figure 2. The incoming WDM channels, containing the packet streams, are first wavelength demultiplexed using an arrayed waveguide grating (AWG). The individual wavelength channels are then sent to an array of optical packet routers. At the packet router part of the signal is picked off in an optical coupler and sent to the optical label decoder, whilst the remaining signal is sent to the optical switch via an appropriate optical delay to compensate for the label processing time. The optical label decoder uses a parallel array of decoders in order to recognise the optical label. The signal from the correctly recognised label is used to control the optical space switch so that the original optical packet is routed to the switch output determined by the label. The routed packets are then recombined in an AWG before continuing through the network.

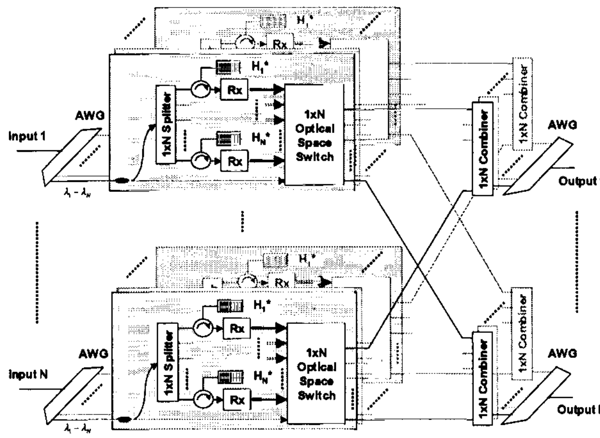

Fig. 2 An NxN multi-wavelength optical packet routing node.

The packet switching system employs an optically coded label that is encoded and decoded all-optically using superstructured fibre Bragg gratings (SSFBG). SSFBGs are single-grating structures onto which a slowly varying amplitude and/or phase pattern (superstructure) is imposed upon a uniform (fast varying), background refractive index modulation. These are fabricated using the "continuous grating writing" technique [6]. This approach only requires a single phase mask with a uniform pitch to write all the different codes into the gratings [9-10]. The phase coding is implemented by introducing discrete phase shifts in the grating between the chips as defined by the code sequences. For a weak SSFBG grating (reflectivity R<20%) such that the light penetrates the full grating length and the individual elements of the grating contribute more or less equally to the reflected response, the shape of the impulse response directly follows the shape of the spatial superstructure profile [6].

The encoding and decoding principle using SSFBGs is illustrated in Figure 3. The optically coded label is created by reflecting a short optical pulse ($I(t)$) off the encoder grating. The encoder grating contains the coding information that is written into its spatial refractive index profile during fabrication. The reflected signal is effectively the impulse response of the encoder grating and contains the code. In this illustration two coded labels are generated $H_1(t)\otimes I(t)\approx H_1(t)$ and $H_2(t)\otimes I(t)\approx H_2(t)$.

Code recognition at the decoder is obtained by matched filtering of the coded signal, using a decoder grating with the time reversed (conjugate) impulse response to that of the encoder grating. Such an impulse response is readily obtained using a grating with exactly the same refractive index profile as the encoder grating and by illuminating it from the opposite end. In this illustration the coded optical pulse is reflected off a decoding grating containing the code $H_1(t)^*$ that is matched to the coded grating $H_1(t)$. The reflected signal from the decoder grating shows a strong correlation peak when the incoming label code is matched to a decoding grating ($H_1(t)^* \otimes H_1(t)$). When the decoding grating is not matched to the incoming signal the cross-correlation results in a low level background as is observed for the gratings combination $H_1(t)^* \otimes H_2(t)$. The cross-correlation with the data payload ($H_1(t)^* \otimes D(t)$) also results in a low level background. An electrical or optical thresholder is used to reject the low-level background terms.

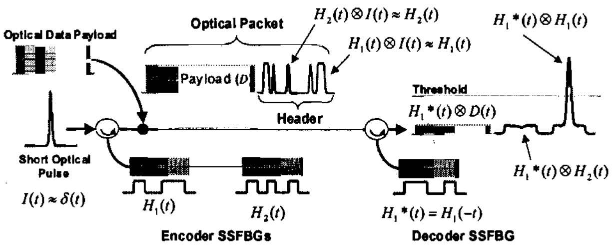

Fig. 3 Schematic showing the principle of optical label encoding and decoding based on SSFBGs.

To achieve high-contrast code recognition features the optical labels (codes) used within this system should exhibit distinct well defined autocorrelation properties, and mutually low cross correlation properties. Quaternary phase coding is used in this experiment since it provides codes with more desirable auto/cross-correlation characteristics than can be achieved with lower order coding schemes such as the unipolar and bipolar code sequences [12]. The SSFBGs used within this experiment allow for the generation of 16-chip, 20 Gchip/s quaternary phase coded pulse sequences [9]. This code length allows for a maximum of 4^{15}-1 distinct address labels to be used per wavelength.

The packet switching experiments presented here use two distinct coded labels denoted as H1 and H2. Figures 4 (a) and (b) show the measured and calculated time domain responses for the two different optical labels generated after reflection from their respective encoding gratings. It can be seen that the encoding gratings spread the incident 20 ps input pulse over a time period of ~800 ps as expected. Excellent agreement can be observed when comparing the experimental data with the theoretical calculations. Figures 5 (a) and (b) illustrate the auto and cross-correlation outputs from decoder grating H1* in response to the optical labels H1 and H2 respectively. As expected, the autocorrelation output (H1:H1*) exhibits a dominant, sharp autocorrelation signature whilst low level, noise-like signals are obtained for the cross-correlation output (H2:H1*) and vice versa. The extinction ratio between the peak of the correctly decoded pulse (Figure 5(a)) and the incorrectly decoded low-level signal (Figures 5(b)) is ~ 8 dB. As a result of the matched filtering correlation process, the decoded output signals have a full duration of 1.6 ns corresponding to twice the encoded duration.

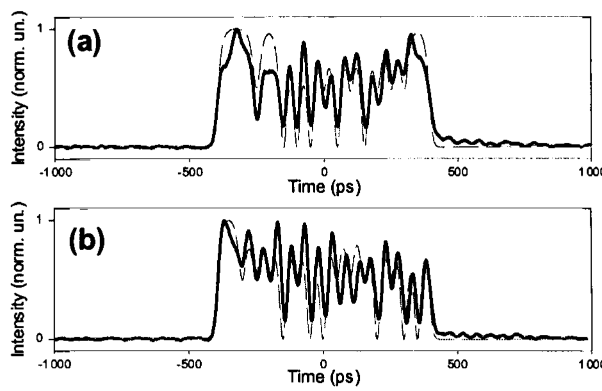

Fig. 4 (a & b) Comparison between the experimentally measured (solid line) and calculated (dashed line) temporal response of the coding gratings H1 and H2 respectively.

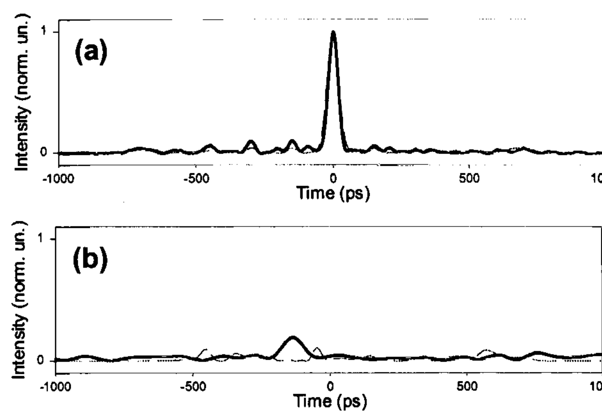

Fig. 5 (a) The autocorrelation response (H1*:H1) after label H1 is reflected from decoder grating H1*. (b) The low level cross-correlation (H1*:H2) resulting from the reflection of label H2 from decoder grating H1*. Solid line – experiment, dashed line – theory.

3. Experimental demonstration

3.1 Multi-wavelength packet transmitter

The schematic of our experimental multi-wavelength packet transmitter is shown in Figure 6. The packet transmitter generates optically coded label pulses, containing the switching codes, which are appended to the front of the data payload to create labelled packets on each of 40 optical wavelengths. Firstly 20 ps duration optical pulses are generated by external modulation of the multiplexed DWDM CW laser sources using an electro absorption modulator (EAM) driven with a 10 GHz sinusoid signal. This is then followed by another modulator acting as a pulse picker to gate the pulses down to the packet rate of 100 Mpps. These pulses are then optically encoded, to produce the optical labels, after reflection off the SSFBG encoders. For convenience a 10 Gbit/s (PRBS 2^7-1) NRZ modulated data payload was used. It should be noted that the packet switching is completely transparent to the bit-rate and the modulation format of the data payload, thus the system will readily support data payloads with higher bit rates. The resulting packets are 10 ns long corresponding to a packet rate of 100 Mpacket/s. The optically coded label is 800 ps in duration, and is separated from the payload by 800 ps guard bands. The label thus occupies 16% of the total packet duration in this implementation (see inset to Figure 6). In this experiment we generated two distinct coded label pulses, denoted by H1 and H2 at each wavelength to reduce the complexity of the set up. These label pulses were also modulated with a 2^7-1 pseudorandom bit pattern in order to produce randomly labelled packets with either label H1, H2 or no label.

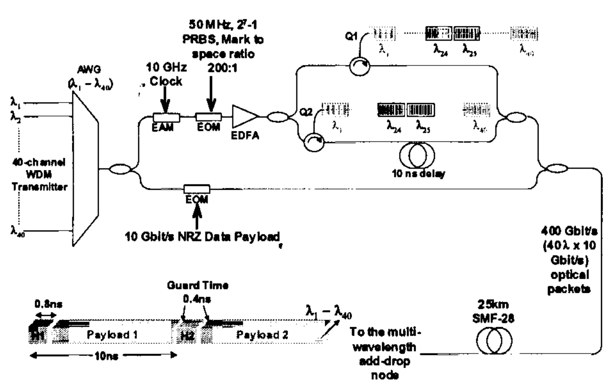

Fig. 6 Experimental WDM packet transmitter set-up used to generate 40 WDM channels each with randomly labeled packets corresponding to codes H1 or H2.

The 400 Gbit/s WDM packet stream was transmitted over a distance of 25 km of standard single mode fibre before entering the multi-wavelength packet switching node.

3.2 Multi-wavelength packet switching node

The packet switching node performs label recognition on the incoming packets in order to determine the correct switching output for each packet. Parallel arrays of decoder gratings (H1* and H2*) are used on each wavelength input of the node to optically decode the label via matched filtering process. The correctly decoded output is then used to control an electro-optic switch so that the incoming packet is correctly routed. Figure 7 shows the setup of our experimental multi-wavelength packet switching node.

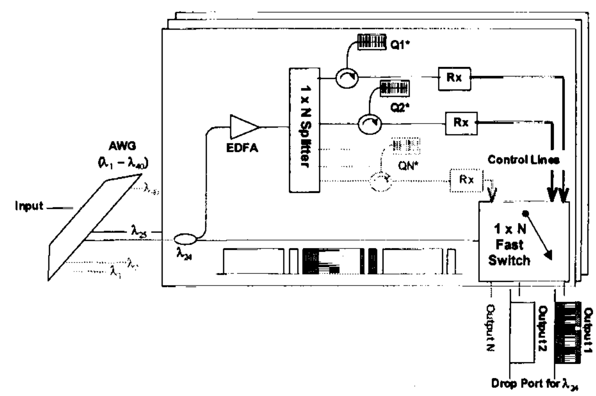

Fig. 7 Experimental set-up for multi-wavelength optical packet router.

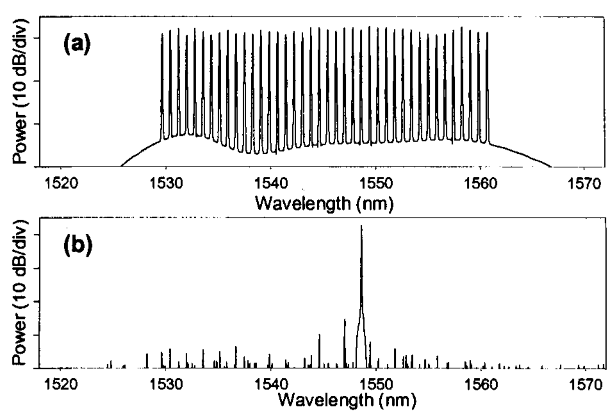

Fig. 8 (a) Optical spectrum incident to the demultiplexing AWG. (b) Optical spectrum of a dropped wavelength channel. The measured resolution was 10pm.

Figure 8(a) shows the optical spectrum of 40 WDM optical packet channels upon entering the add/drop node. Wavelength demultiplexing is first performed using the AWG. An extinction ratio of ~30 dB is obtained as shown in Figure 8(b).

Optical label recognition is performed independently for each wavelength channel in order to control the switching of the data. Part of the incoming packet stream is sent to the label-decoder which consists of an array of fibre gratings H1* and H2* whose codes are matched to the encoding gratings in the transmitter (H1 and H2). For example, if label recognition is carried out by reflecting the packets (shown in Figure 9(a)) off decoding grating H1* a strong correlation peak H1:H1* arises from label H1 as shown in Figure 9(b). There is also some residual background arising from the cross-correlation between label H2 and the decoding grating H1*, and a contribution from the reflected data payloads also shown in Figure 9(b). The detected signal is then electrically thresholded and used to control the electro-optic switch. In this experiment the detection of labels H1 or H2 sets the switch so that the packet is routed out of ports 1 or 2 respectively. The correctly routed packets at output ports 1 and 2 are shown in Figures 9(c) and (d) respectively.

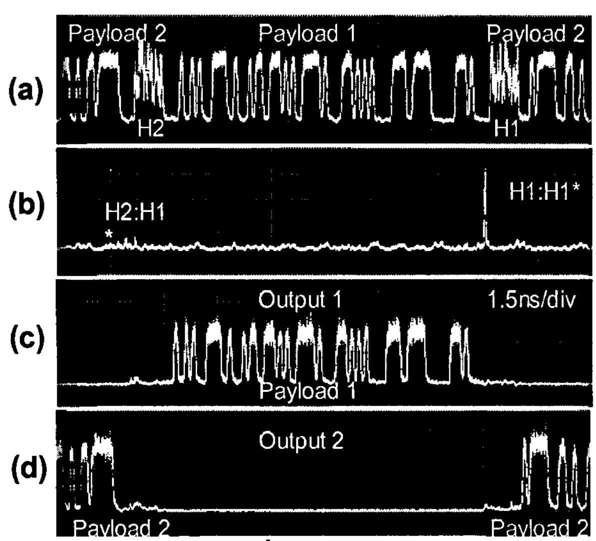

Fig. 9 (a) Packet structure at a particular wavelength showing the labels (H1 and H2) and their associated packets. (b) Corresponding decode signal after matched filtering using decoder grating H1*. (c & d) Switched packets at output ports 1 and 2 respectively.

The quality of the label recognition is characterised by measuring the bit error rate (BER) of the label recognition process. The results are plotted in Figure 10(a) and show that no power penalty can be observed when comparing with laser back-to-back measurements. Figure 10(b) shows the BER measurements made on the routed packets in the presence of multiple DWDM wavelengths. Again, error free performance is obtained for all of the measured channels, even in the instance that all 40 channels are transmitting simultaneously.

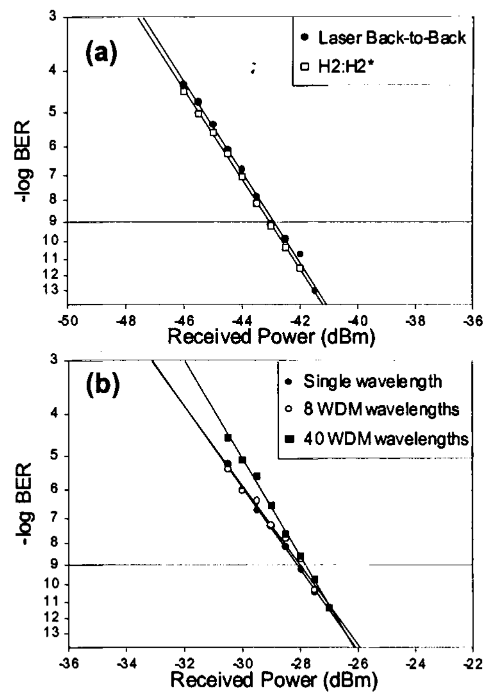

Fig. 10 (a) BER of label recognition in the absence of the attached payloads and DWDM MUX:DEMUX. (b) BER of the packet recognition for the full system in the presence of multiple DWDM wavelengths.

4. Conclusions

We have experimentally demonstrated a multi-wavelength packet routing node capable of high packet processing capacity (> 4 Gpps) and aggregate data capacity (currently 0.4 Tbit/s but readily upgradeable to the multi Tbit/s level). SSFBGs provide an extremely powerful and flexible technology that is well suited to performing the optical processing functions required within all-optical packet switched networks.

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