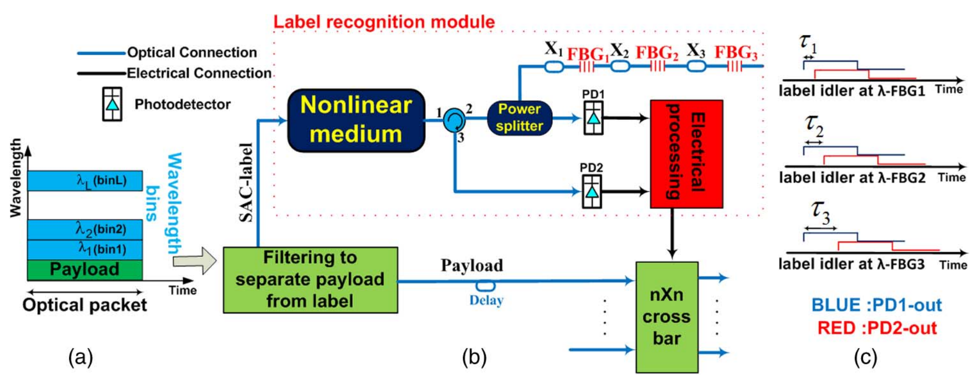
IEEE Photonics Journal
An IEEE Photonics Society Publication

Novel FWM-Based Spectral Amplitude Code Label Recognition for Optical Packet-Switched Networks

Volume 5, Number 4, August 2013

S. Alireza Nezamalhosseini
Mohammad Rezagholipour Dizaji
Kerim Fouli
Lawrence R. Chen, Senior Member, IEEE
Farokh Marvasti, Senior Member, IEEE



DOI: 10.1109/JPHOT.2013.2274769

Novel FWM-Based Spectral Amplitude Code Label Recognition for Optical Packet-Switched Networks

S. Alireza Nezamalhosseini,[1,2] Mohammad Rezagholipour Dizaji,[1] Kerim Fouli,[3] Lawrence R. Chen,[3] *Senior Member, IEEE*, and Farokh Marvasti,[3] *Senior Member, IEEE*

[1]Department of Electrical and Computer Engineering, McGill University, Montreal, QC H3A 0E9, Canada
[2]Department of Electrical Engineering, Sharif University of Technology, Tehran 11365-9363, Iran
[3]Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139 USA

DOI: 10.1109/JPHOT.2013.2274769
1943-0655 © *2013 IEEE*

Manuscript received June 26, 2013; revised July 17, 2013; accepted July 17, 2013. Date of publication July 25, 2013; date of current version August 7, 2013. This work was supported in part by the Natural Sciences and Engineering Research Council (Canada) via the CREATE program on Next-Generation Optical Networks, as well as the Ministry of Higher Education and the Iran Telecom Research Center (ITRC). Corresponding author: S. A. Nezamalhosseini (e-mail: alireza.nezam@gmail.com; nezam_ar@yahoo.com).

Abstract: We propose and demonstrate a novel architecture for four-wave mixing (FWM)-based recognition of spectral amplitude code (SAC) labels in optical packet-switched networks. With a proper code design, a unique FWM idler for each SAC label, referred to as a label identifier (LI), is generated in a nonlinear medium. A serial array of fiber Bragg gratings is then used to reflect the LI wavelengths. Each LI is associated with a unique amount of delay between two optical signals received at two photodiodes (PDs). Label recognition is then achieved by measuring this unique time delay (referred to as the characteristic delay). The main advantages of the proposed method include the following: no serial-to-parallel conversion is required, simple label extraction is achieved, variable-length packets are supported, and the number of PDs used in the label recognition module is reduced. Moreover, the LI wavelengths do not need to exhibit any periodicity or match a particular wavelength grid; this results in a less challenging code design with smaller spectral occupancy for label generation. An experiment is conducted, where two variable-length data packets are transmitted over a 50-km dispersion-compensated span and switched at a forwarding node. The SAC labels are successfully recognized, and we obtain error-free transmission for the switched packets with less than 0.3-dB penalty.

Index Terms: Optical packet switching, four wave mixing (FWM), label recognition, spectral amplitude codes (SACs).

1. Introduction

Current fiber optic transmission systems are based on wavelength switching (WS), where forwarding is performed using reconfigurable optical add drop multiplexers (ROADMs) and optical cross-connects (OXCs). Bursty applications such as IPTV, video conferencing, storage area networks, tele-medicine, and tele-education result in the ever increasing growth of data traffic. This bursty data traffic, combined with the inefficient coarse granularity of wavelength switches, makes optical packet switching (OPS) attractive to achieve fine granularity, high bandwidth efficiency, and high network utilization [1]–[5] and it is a topic of intense research.

In OPS networks, electrical nodes located at the network periphery are connected to the optical network via edge nodes. Electrical packets are converted to optical packets at the edge nodes. Optical packets are then routed in the core network, on a hop-by-hop basis. The advent of generalized multi-protocol label switching (GMPLS) has been one of the most promising advances in packet-switched systems as it enables high-speed optical packet transmission [6]. In GMPLS, high-speed optical packet forwarding can be achieved due to the separation of forwarding and control operations [7]. Furthermore, payloads are optically switched at forwarding nodes without undergoing optical-to-electrical-to-optical (OEO) conversion. This makes GMPLS-based optical switches transparent to payload data rates, modulation formats, and protocols (e.g., IP, ATM, SONET, etc.). The routing paths are determined at the edge nodes, and the forwarding nodes are responsible for forwarding the packets towards the destination, based on the optical label [8] (see also Fig. 2 in [9]). Hence, the forwarding nodes require several switching functionalities such as label recognition, label swapping, synchronization, and contention resolution. The implementation of high-speed OPS with conventional electronic recognition modules has been the subject of intense research, with techniques including the use of time domain labels [10], [11], amplitude-shift-keying (ASK) labels [12], bit-parallel labels [13], frequency-shift-keying (FSK) labels [14], and subcarrier modulated (SCM) labels [15]. A problem associated with these techniques is forwarding node latency, caused by the electronic processing time required for label identification.

To overcome forwarding node latency, optical-code-division multiple-access (OCDMA) codes were proposed as optical labels [16]–[19]. One such set of codes are spectral amplitude codes (SACs) [20]–[22]. For SAC labeling techniques, typically the wavelengths (or wavelength bands) used to define the payload and the labels do not overlap which facilitates simultaneous transmission and subsequent processing of the label and payload. The label is modulated at the packet rate and can be present for the entire packet duration. Label extraction can be performed by simple optical filtering. As such, label recognition can be performed without modifying the payload. Note further that in this implementation, the forwarding node is transparent to modulation format, bit rate, and protocol of the payload.

A single-processor four-wave mixing (FWM)-based SAC label recognition technique was proposed in [22] to avoid the need for parallel matched filters (MFs), which is often the approach adopted for decoding OCDMA signals or recognizing OCDMA labels. In [22], weight-2 labels are considered, i.e., each optical label contains two wavelengths selected from a bin of L available wavelengths. By passing the extracted optical label through a nonlinear medium, FWM idlers are generated. A proper code design is achieved if for each SAC label, at least one of the generated FWM idlers is unique and does not overlap with (1) any of the generated idlers from the other labels and (2) one of the original L available wavelengths. This unique idler is referred to as the label identifier (LI). An arrayed waveguide grating (AWG) is then used to isolate the unique LIs from which a suitable electronic control signal is generated. Fig. 1(a) shows an example of recognizing a SAC label using its corresponding unique LI [22]. In this example, three different weight-2 SAC labels are generated from a bin of three equally spaced wavelengths.

However, owing to the fixed and equal wavelength spacing between AWG outputs, increasing the number of labels makes it more difficult to select wavelengths that will generate unique LIs that satisfy the above-mentioned criteria. Furthermore, in [22], the number of photodiodes (PDs) grows with the number of labels, thus increasing complexity and limiting scalability. In order to overcome these issues, we propose and demonstrate a new architecture for recognizing SAC labels based on FWM in which FBGs are used instead of AWGs. Our approach provides more freedom in selecting the wavelength set for labels and also avoids potential wavelength interference which occurs (or is more likely to occur) when fixed and equally-spaced wavelengths are used. The reduction in interference comes from the flexibility of the design associated with removing the fixed wavelength separation constraint, which also makes it easier to place and isolate the LIs in a separate band, as shown in Fig. 1(b). Moreover, in our label recognition structure, only two PDs are necessary regardless of the number of labels, thus improving device scalability (see Section 4). We verify experimentally successful label recognition, switching, and transmission of 10 Gb/s packets over a 50 km dispersion compensated transmission span.

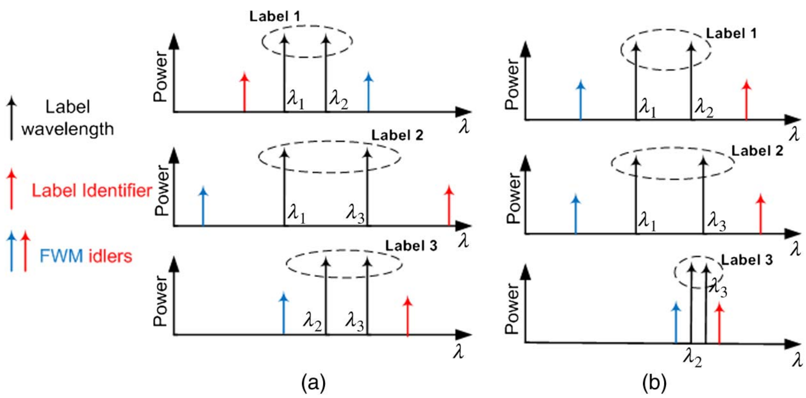


Fig. 1. SAC label recognition by unique LI allocation in (a) an AWG based structure; (b) the proposed FBG based structure.

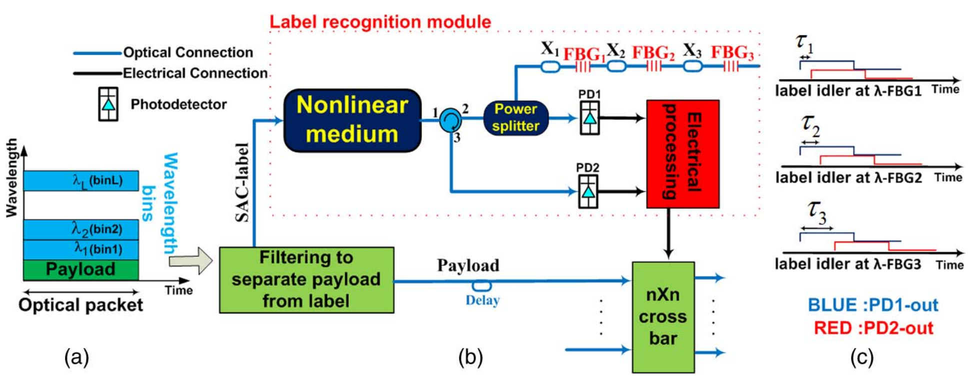


Fig. 2. Schematic diagram of a forwarding node including the proposed SAC label recognition technique (a) optical packet; (b) label recognition module; (c) different characteristic delays for labels.

The remainder of this paper is organized as follows. In Section 2, we describe our label recognition architecture. Section 3 details the experimental setup and demonstrated results. Section 4 contains a discussion of the experiment as well as the major benefits of our architecture and potential future work. Finally, we summarize and conclude in Section 5.

2. Proposed Label Recognition Technique

Fig. 2 demonstrates the general schematic of a forwarding node in which the proposed label recognition module is incorporated. As shown in Fig. 2(a), a SAC label is formed by choosing a subset of wavelengths from a bin of L available wavelengths. Each SAC label can be represented as a vector of length L as follows:

$$Label_j = \left(A_j^1, A_j^2, \ldots, A_j^L\right) \tag{1}$$

where A_j^k is the amplitude (i.e., 0 or 1) of the kth wavelength in Label j. In our approach, we exploit degenerate FWM between the wavelengths of a SAC label in the label recognition process; hence, codes having two active wavelengths are considered (weight-2 codes), resulting in a total of $\binom{L}{2}$ SAC labels. Each packet comprises one payload and one label that are transmitted simultaneously. The packets can have different durations and support payloads of different modulation formats and bit rates.

To identify the LI associated with a SAC label, we propose the label recognition module shown in Fig. 2(b). The label recognition module comprises a nonlinear medium in which FWM occurs to

TABLE 1

Parameters of the experimental demonstration involving recognition of two variable length packets. The idler wavelength highlighted in bold is used as the LI

Packet Number	Label Wavelength1 (nm)	Label Wavelength2 (nm)	FWM idler1 (nm)	FWM idler2 (nm)	Characteristic delay (ns)	Packet duration (μs)
1	1535.152	1535.818	1534.48	**1536.48**	35	1
2	1538.975	1539.368	1538.58	**1539.76**	80	0.5

generate the LI, a circulator, an optical coupler, a serial FBG array, and two PDs. The output of the nonlinear medium reaches the optical coupler via the circulator. The signal from one branch of the optical coupler (i.e., a copy of the output from the nonlinear medium) is detected immediately by PD1. The second branch of the coupler is connected to a serial array of FBGs with reflection wavelengths corresponding to the LIs. The FBGs are physically separated by short lengths of fiber (denoted X_n). If the input SAC label generates the ith LI at the output of the nonlinear medium, it will be reflected by the corresponding FBG back through the optical coupler and the circulator before detection at PD2. The detected signal at PD2 will appear at a delay τ_i with respect to the signal received by PD1. τ_i, referred to as the characteristic delay, is uniquely associated with the ith LI and is proportional to the total length of fiber that the LI wavelength propagates in the module. Thus, the spectral information contained in each of the different labels is translated into a unique time delay detected by the two PDs. The LIs are then identified using a simple electronic processor that measures the characteristic delay. Fig. 2(c) shows an example of different characteristic delays for different labels.

3. Experimental Setup and Results

We verify operation of the proposed SAC label recognition module in a systems-level experiment. In our demonstration, two packets, each with a fixed packet size and data rate, are merged at a packet generator and subsequently separated at a forwarding node. We choose two weight-2 SAC labels with the following label wavelengths: 1535.15 nm and 1535.81 nm for Label 1 and 1538.97 nm and 1539.36 nm for Label 2. The label wavelengths are chosen so that the generated LIs correspond to the reflection wavelengths of FBGs that we have available. Note that the spacing between the label wavelengths is not the same for the two SAC labels which is accommodated by the flexible nature of code design based on our proposed approach. Table 1 summarizes the packet parameters.

The payload wavelength is located at 1537.48 nm, in the intraband of the SAC labels. Fig. 3 shows a schematic of the experimental setup. At the transmitter, two separate pattern generators (PGs) are used to form the two packets. The durations of Packet 1 and Packet 2 are 1 μs and 0.5 μs, respectively, and the packets are separated by 0.25 μs. Two separate laser sources, both tuned to the payload wavelength of 1537.48 nm, are modulated by a $2^{15} - 1$ pseudo random binary sequence (PRBS) using separate Mach-Zehnder modulators (MZM2 and MZM3) to generate 10 Gb/s NRZ-OOK data as the payloads for Packet 1 and Packet 2, respectively. The labels for the two packets are generated by modulating the output from the lasers at the label wavelengths using MZM1 and MZM4 (as described above, the labels are modulated at the packet rate, i.e., the label is ON for the packet duration). The PGs are set to synchronize the label and payload for each packet. The two PGs are also synchronized with respect to each other to provide the 0.25 μs gap. Fig. 4(a) shows an oscilloscope trace of the two packets at the transmitter (point A of the setup). The packets are then transmitted through a span consisting of 50 km of single mode fiber (SMF) followed by a dispersion compensating module (DCM). EDFAs amplify the signal before the SMF and after the DCM. The launch power into the SMF is -1.8 dBm.

The packets then reach the forwarding node where a 3 dB coupler is used to provide copies of the received packets to the payload branch and the label recognition module. In the payload branch, the payloads are separated from the labels using a 0.66 nm bandpass filter (BPF); Fig. 4(b)

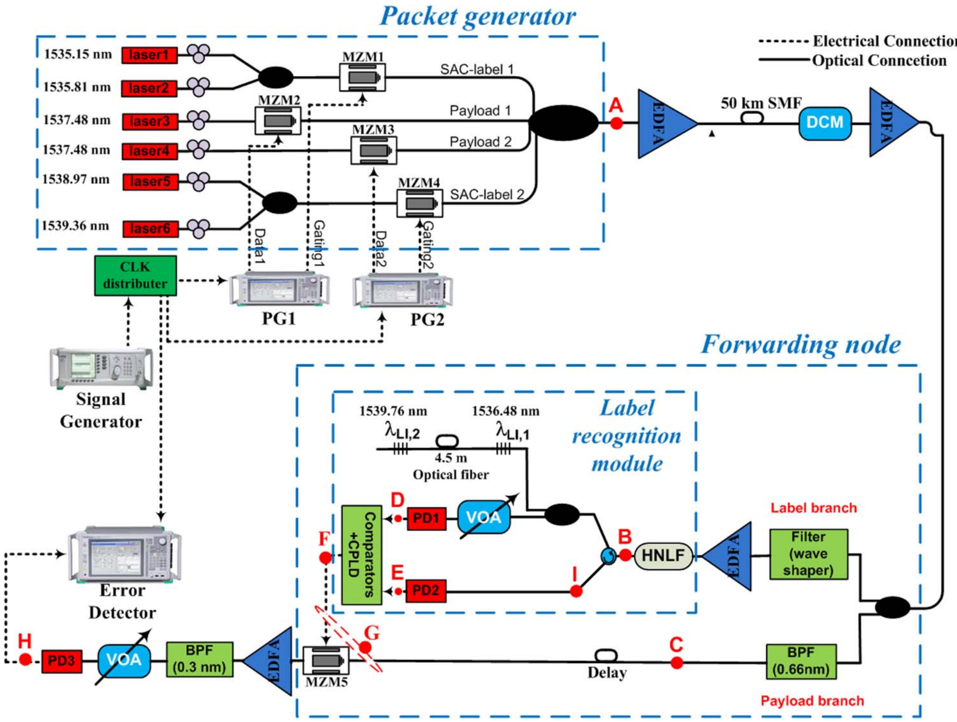


Fig. 3. Experimental setup of the packet switching with SAC-labels. MZM: Mach-Zehnder Modulator, EDFA: Erbium-doped fiber amplifier, DCM: dispersion-compensating module, HNLF: Highly NonLinear Fiber, VOA: Variable Optical Attenuator, BPF: BandPass Filter, PD: PhotoDiode, CPLD: Complex Programmable Logic Device.

shows the payloads from both packets at point C. The payloads then experience a delay equal to the required processing time for the label [this corresponds largely to the propagation time of the label through the HNLF and can be reduced significantly using a shorter length nonlinear medium such as a semiconductor optical amplifier (SOA)]. The payloads then pass through MZM5 which emulates an optical switch and is driven by an electronic signal obtained from the label recognition module.

In the label branch, a notch filter (Finisar Waveshaper 1000 S) is used to extract the two SAC labels while blocking the payload. The labels are input to the nonlinear medium comprising 1 km of HNLF to generate the FWM idlers (the input power to the HNLF is 12.5 dBm). Fig. 5(a) shows the measured spectrum of the SAC labels and their FWM idlers at point B within the label recognition module. The output from the HNLF passes through a circulator and a 3 dB coupler. The output on one branch of the coupler is detected immediately by PD1. The output from the second branch of the coupler is launched into a serial array of two FBGs with reflection wavelengths at 1536.48 nm and 1539.76 nm. The reflected signal then reaches PD2 through the circulator. Fig. 5(b) shows the measured spectrum at point I. In order to equalize the power levels of the signals appearing at both PDs, a variable optical attenuator (VOA) is used before PD1. Fig. 4(c) and (d) show the electrical output of PD1 and PD2, respectively (i.e., at points D and E). These electrical signals are then sent to the electronic processor which is programmed to detect a specific label and generate a corresponding electronic control signal based on the characteristic delay. Fig. 6 shows a schematic of the electronic processor, which contains two slow 150 MHz analog comparators followed by a complex programmable logic device (CPLD).

The electronic processor generates a control signal for the duration of the identified label in order to permit the corresponding data payload to be switched by MZM5. Since the SAC labels are modulated at the packet rate and the control signal is ON for the time equal to the corresponding packet, this scheme is capable of processing variable length packets. Fig.4 (e) and (f) show the

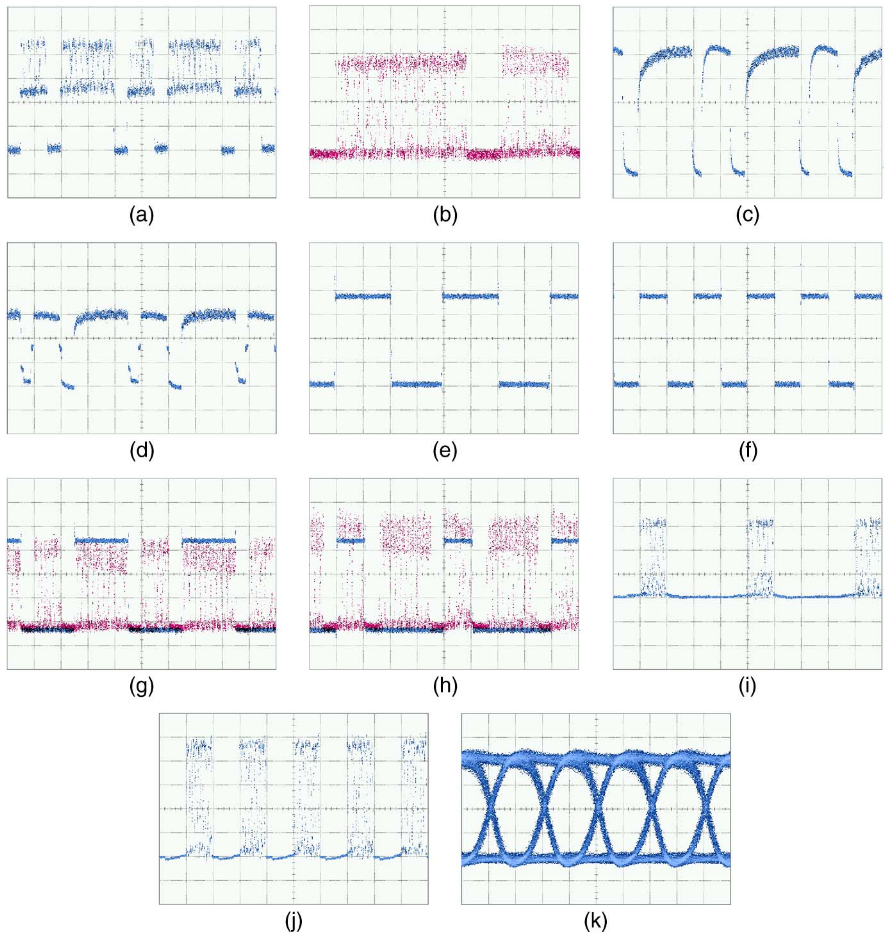


Fig. 4. Oscilloscope traces of (a) generated packets (Fig. 3, point A, 500 ns per division), (b) payloads extracted by BPF (Fig. 3, point C, 200 ns per division), (c) (Fig. 3, point D, 500 ns per division), (d) (Fig. 3, point E, 500 ns per division), (e) electronic control signal for 1 μs packets (Fig. 3, point F, 500 ns per division), (f) electronic control signal for 0.5 μs packets (Fig. 3, point F, 500 ns per division), (g) payloads and 1 μs electronic control signal (Fig. 3, point G, 500 ns per division), (h) payloads and 0.5 μs electronic control signal (Fig. 3, point G, 500 ns per division), (i) 0.5 μs packets switched by control signal (Fig. 3, point H, 1000 ns per division), (j) 1 μs packets switched by control signal (Fig. 4, point 3, 500 ns per division). (k) shows the eye-diagram of packet 2 after switching (with dispersion compensation).

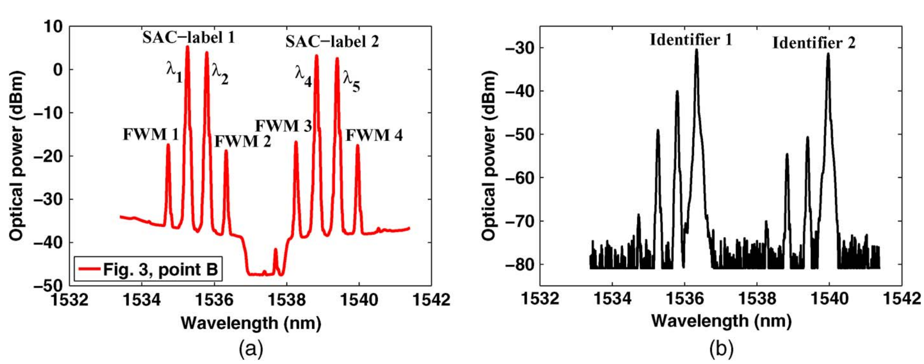


Fig. 5. Optical spectrum analyzer traces of (a) SAC-labels and their FWM idlers, (Fig. 3, point B); (b) FWM idlers reflected back by FBGs (Fig. 3, point I).

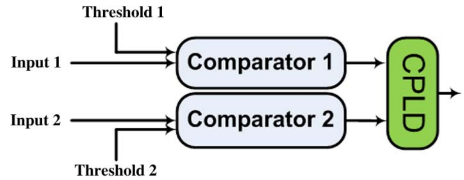


Fig. 6. The schematic of the electronic processing part.

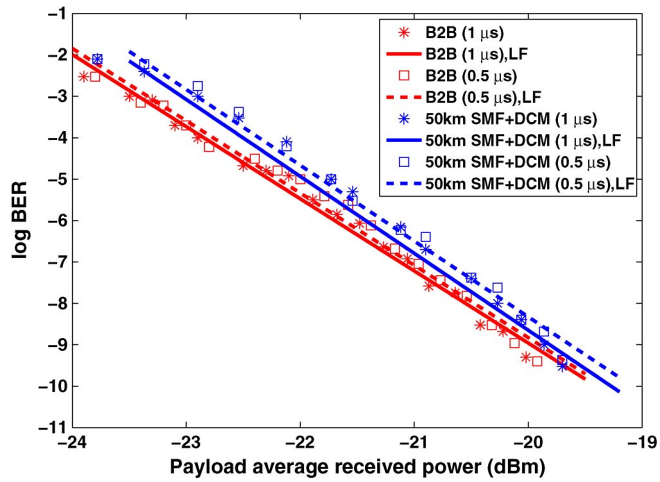


Fig. 7. BER for the payloads of Packets 1 and 2. The solid and dashed lines correspond to the 1 and 0.5 μs payloads, respectively. LF : Linear Fitting.

control signals generated for Packet 1 and Packet 2, respectively. Fig. 4(g) and (h) show the control signals for Packet 1 and Packet 2 overlaid with the payloads at the input of MZM5 (point G). Fig. 4(i) and (j) show the switched payloads of Packet 1 and Packet 2, respectively, at the output of the MZM5 (point H). Finally, Fig. 7 shows the measured bit error rate (BER) for the payloads of Packets 1 and 2. Error-free transmission is obtained, and the switched payloads exhibit a power penalty of only 0.3 dB compared to the back-to-back case. Fig. 4(k) shows the eye diagram for the payload of Packet 2 after switching.

4. Discussion

In our experiment, we only use 2 SAC labels in order to demonstrate the operation of our label recognition module. To generate the 2 SAC labels, we used 4 wavelengths, where 2 non-overlapping wavelengths were used for each label. In practice, we could have generated SAC labels with one overlapping wavelength or different wavelength spacings; we were constrained only by the center wavelengths of the FBGs available. We also used two packets separated by a gap of 0.25 μs. This gap can be reduced (e.g., to a few *ns*) by having a constant delay in the payload branch to compensate the label recognition time for the packet with the largest characteristic delay. As mentioned above, this delay corresponds largely to the propagation time of the label through the nonlinear medium. The gap can be reduced further by employing a higher speed electronic processor. A minimum gap is required for the electronic processor to distinguish between two consecutive payloads in a stream of bits. Also proper flagging of the beginning and the end of packets can help to distinguish two consecutive packets while minimizing the gap between them. Furthermore, the processing delay associated with propagating the label signal through the HNLF requires us to use a delay fiber for synchronizing the switching signal with the payload at MZM5 as depicted in Fig. 3. To reduce this delay, the HNLF can be replaced by an SOA. Also, when using an SOA as the nonlinear

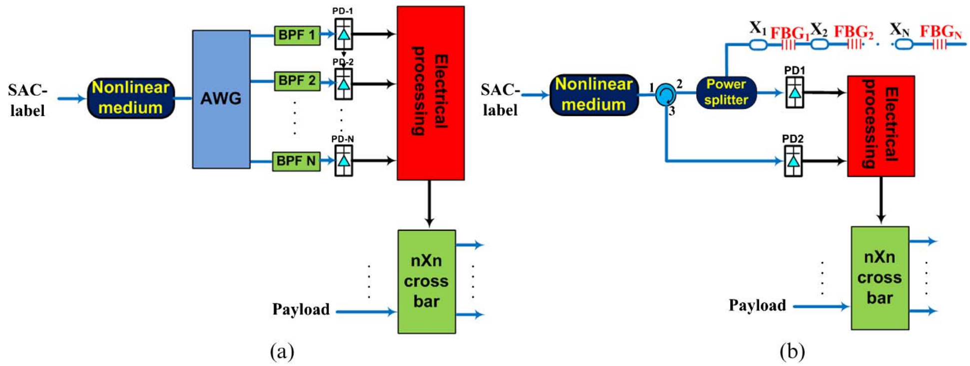


Fig. 8. FWM based SAC label recognition structures: (a) in an AWG based architecture; (b) using our proposed architecture. In both cases *N* labels can be generated.

medium, it should be possible to reduce the power consumption as the input power required to generate nonlinear effects (e.g., FWM) in properly designed SOAs is lower than for HNLF.

Ultrafast label recognition is achieved due to the FWM process. The proposed technique is based on a single processor approach in which no serial-to-parallel conversion occurs. Therefore power splitting losses, copying of incoming labels, and multiple MFs are not issues with our method. Moreover, greater scalability can be achieved compared to parallel label recognition techniques. Fig. 8 compares the AWG based label recognition technique in [22] with our proposed structure. As shown in Fig. 8(b), the number of required FBGs for our label recognition technique is equal to the number of SAC labels, where the number of PDs and electronic comparators is always 2 regardless of the cardinality of the code. In contrast, using AWGs, the number of PDs is proportional to the number of LIs, as stated in Section 1 and illustrated by Fig. 8(a). It should be noted that scalability can be achieved using hierarchical addressing and photonic integration. In hierarchical addressing, orthogonal frequency bands can be allocated to various label sections corresponding to different network domains. The related label section to each network domain can be easily extracted using the optical filters. This extracted label is used for optical switching. Therefore, the number of optical labels in each network domain and hence the number of required FBGs in each intermediate node will be reasonable. Moreover, it is possible to develop an integrated serial array of Bragg gratings. For example, we have recently demonstrated a serial array of 5 sidewall gratings in SOI with tens of *ps* delay between reflection wavelengths [24]. Cascading additional gratings should be possible; longer delays can be achieved however, values in excess of several *ns* will be challenging and propagation losses (typically 1.5 dB/cm to 2.5 dB/cm) will impose further constraints. A detailed analysis and discussion of integrating our proposed label recognition structure is beyond the scope of this paper.

In order to increase the code cardinality, a bin comprising more wavelengths can be used. In other words, increasing the code cardinality will come at the expense of using more wavelength bins and hence reducing the spectral efficiency. An advantage of our SAC label recognition technique is the freedom of selecting wavelengths for the bin as they need not be equally spaced. This gridless nature of our SAC label code design is provided by using FBGs instead of AWGs. In AWG based SAC label recognition techniques, the wavelength separations are constant, hence the FWM idlers of any SAC labels also appear in multiples of these separation units. Therefore, as mentioned previously, two different cases should be considered in order to design proper SAC codes for a bin of equally spaced wavelengths: (1) at least one of the FWM idlers of a SAC code should not overlap with any active wavelengths in the bin and (2) the LIs for different codes must not overlap with each other. In our FBG-based approach, due to unequal separation of wavelength bins, the first mentioned concern can be easily avoided. Also the coincidence of LIs for different labels is not as likely as for the case of equally spaced wavelengths (as in the AWG-based approach). Therefore as the number of labels is increased, finding unique LIs for our technique is less challenging compared to techniques using AWGs, making our technique more scalable. It is worth mentioning that there is no need to have equal power LIs for different codes. The power in the LIs should only be sufficient to prevent false alarms and ensure that the probability of a missed detection is low. As such, the minimum power of LIs must be above the noise power and the corresponding minimum required optical signal-to-noise ratio can be set accordingly.

The removal of parallel processing through FBGs, and the ensuing shift of label/code recognition from the wavelength domain (LI detection) to the time-domain (electronic delay computation), greatly increases the flexibility and simplicity of our design. This makes it particularly attractive in situations with high scalability requirements, where a single detector/decoder is used to distinguish a large number of coded signals, such as large optical packet/burst switches or centralized all-optical monitoring systems [23]. Indeed, the time-domain processing involved makes our design more suitable for optical coding applications than for conventional OCDMA, where decoding is required at the data rate [18]. Finally, it should be mentioned that one of the drawbacks of the proposed method is the spectral occupancy tradeoff against the code cardinality. However, network agility and fine granularity that would be enabled by OPS networks will increase the overall network throughput.

5. Summary and Conclusion

In this paper, we have proposed a single label recognition module for OPS networks using low weight SAC labels. The label recognition is performed based on the LIs which are generated using a nonlinear device. A simple configuration including a serial array of FBGs and a low-speed electronic module identifies any incident LI by converting it into a unique characteristic delay that can be detected using a small number of PDs. This enables the electronic module to generate a control signal for the optical switch. Since the label is ON for the entire duration of the packet and switching the packet is controlled by the label duration, this approach can be used to support variable packet length in the network. Another important advantage of the proposed method is to avoid the complexity of provisioning codes where the FWM idlers adhere to a pre-established standard grid of wavelengths. This problematic arises when AWGs are to be used as filters that distinguish the FWM idlers. FBGs are not subject to the strict grid requirements of AWGs. Moreover, the proposed method does not use parallel processing, hence avoiding consequent insertion losses and improving scalability.

We experimentally demonstrated successful forwarding of packets after transmission over 50 km SMF and dispersion compensation. Label recognition was performed without any errors, and error-free transmission was achieved for 10 Gb/s NRZ-OOK data with less than 0.3 dB penalty at a BER of 10^{-9}. These results show the feasibility of the proposed technique in OPS networks. This architecture may readily be extended to other applications with high-scalability requirements such as all-optical monitoring.

Acknowledgment

The authors wish to thank Benjamin Nahill and Omid Sarbishei from the Integrated Microsystems Lab. at McGill University for their valuable help on assembling and programming the electronic processing unit.

References

[1] M. J. O'Mahony, D. Simeonidou, D. K. Hunter, and A. Tzanakaki, "The application of optical packet switching in future communication networks," *IEEE Commun. Mag.*, vol. 19, no. 3, pp. 128–135, Mar. 2001.
[2] N. Kataoka, K. Sone, N. Wada, Y. Aoki, S. Kinoshita, H. Onaka, T. Miyazaki, and K. Kitayama, "Experimental demonstration of multicast-capable variable bandwidth colored packet switching using SOA switch and stacked OC label processing," presented at the Optical Fiber Communication Conf. (OFC/NFOEC), San Diego, CA, USA, 2008.
[3] N. Kataoka, K. Sone, K. Kaneko, T. Aoyama, K. Shimizu, T. Kawano, M. Maruyama, N. Wada, Y. Aoki, S. Kinishita, H. Otsuki, H. Harai, H. Onaka, T. Miyazaki, and K. Kitayama, "4K uncompressed streaming over multicast-capable $80(8\lambda \times 10)$ Gbps colored optical packet switching network using SOA switch and stacked OC-label processing," presented at the Optical Fiber Communication Conf. (OSA/OFC/NFOEC), San Diego, CA, USA, 2009, Paper OWK3.

[4] N. Calabretta, "FPGA-based label processor for low latency and large port count optical packet switches," *J. Lightw. Technol.*, vol. 30, no. 19, pp. 3173–3181, Oct. 2012.
[5] N. Kitayama, N. Kataoka, S. Yoshima, N. Wada, H. Onaka, and G. Cincotti, "Optical code label switching and its applications," in *Proc. Photon. Switch. Conf.*, 2006, pp. 1–3.
[6] A. Banerjee, J. Drake, J. P. Lang, B. Turner, K. Kompella, and Y. Rekhter, "Generalized multiprotocol label switching: An overview of routing and management enhancements," *IEEE Commun. Mag.*, vol. 39, no. 1, pp. 144–150, Jan. 2001.
[7] U. Black, *MPLS and Label Switching Networks,* 2nd ed. Englewood Cliffs, NJ, USA: Prentice-Hall, 2002.
[8] S. J. B. Yoo, "Optical packet and burst switching technologies for the future photonic Internet," *J. Lightwave Technol.*, vol. 24, no. 12, pp. 4468–4492, Dec. 2006.
[9] S. J. B. Yoo, "Energy efficiency in the future Internet: The role of optical packet switching and optical-label switching," *IEEE J. Sel. Topics Quantum Electron.*, vol. 17, no. 2, pp. 406–418, Mar./Apr. 2011.
[10] J. E. McGeehan, M. C. Hauer, A. B. Sahin, and A. E. Willner, "Multiwavelength-channel header recognition for reconfigurable WDM networks using optical correlators based on sampled fiber Bragg gratings," *IEEE Photon. Technol. Lett.*, vol. 15, no. 10, pp. 1464–1466, Oct. 2003.
[11] K. Chan, F. Tong, C. K. Chan, L. K. Chen, and W. Hung, "An all-optical packet header recognition scheme for self-routing packet networks," in *Proc. Opt. Fiber Commun. Conf.*, 2002, pp. 284–285.
[12] Y. Lin, M. Yuang, S. Lee, and W. Way, "Using superimposed ASK label in a 10-Gb/s multihop all-optical label swapping system," *J. Lightw. Technol.*, vol. 22, no. 2, pp. 351–361, Feb. 2004.
[13] T. Lin, K. A. Williams, R. V. Penty, I. H. White, M. Glick, and D. McAuley, "Performance and scalability of a single-stage SOA switch for 10 $\times$ 10 Gb/s wavelength striped packet routing," *IEEE Photon. Technol. Lett.*, vol. 18, no. 5, pp. 691–693, Mar. 2006.
[14] E. N. Lallas, N. Skarmoutsos, and D. Syvridis, "Coherent encoding of optical FSK header for all optical label swapping systems," *J. Lightw. Technol.*, vol. 23, no. 3, pp. 1199–1209, Mar. 2005.
[15] M. Y. Jeon, Z. Pan, J. Cao, Y. Bansal, J. Taylor, Z. Wang, V. Akella, K. Okamoto, S. Kamei, J. Pan, and S. J. B. Yoo, "Demonstration of all-optical packet switching routers with optical label swapping and 2R regeneration for scalable optical label switching network applications," *J. Lightw. Technol.*, vol. 21, no. 11, pp. 2723–2733, Nov. 2003.
[16] K. Kitayama and N. Wada, "Photonic IP routing," *IEEE Photon. Technol. Lett.*, vol. 11, no. 12, pp. 1689–1691, Dec. 1999.
[17] N. Wada and F. Kubota, "Cutting edge technologies on broadband and scalable photonic-network—Packet switched networks based on all-optical label processing," *Opt. Rev.*, vol. 11, no. 2, pp. 106–112, Mar. 2004.
[18] K. Fouli and M. Maier, "OCDMA and optical coding: Principles, applications, and challenges," *IEEE Commun. Mag.*, vol. 45, no. 8, pp. 27–34, Aug. 2007.
[19] J. A. Salehi, "Emerging OCDMA communication systems and data networks," *J. Opt. Netw.*, vol. 6, no. 9, pp. 1138–1178, Sep. 2007.
[20] P. Seddighian, S. Ayotte, B. Rosas-Fernandez, J. Penon, S. LaRochelle, and L. A. Rusch, "Label stacking using spectral amplitude code labels for optical packet switching," presented at the Optical Fiber Communication Conf. (OFC), Anaheim, CA, USA, 2006, Paper JThB.
[21] N. Calabretta, J. Hyun-Do, J. Llorente, E. Tangdiongga, T. Koonen, and H. Dorren, "All-optical label swapping of scalable in-band address labels and 160-Gb/s data packets," *J. Lightw. Technol.*, vol. 27, no. 3, pp. 214–223, Feb. 2009.
[22] J. B. Rosas-Fernández, S. Ayotte, L. A. Rusch, and S. LaRochelle, "Ultrafast forwarding architecture using a single optical processor for multiple SAC-label recognition based on FWM," *J. Sel. Topics Quantum Electron.*, vol. 14, no. 3, pp. 868–878, May/Jun. 2008.
[23] K. Fouli, R. Chen, and M. Maier, "Time-, wavelength-, and code-domain optical reflection monitoring for next-generation access-metro networks," *J. Comput. Commun.*, vol. 34, no. 8, pp. 1011–1021, Jun. 2011.
[24] M. Spasojevic and L. R. Chen, "Discretely tunable optical delay lines using serial and step-chirped sidewall Bragg gratings in SOI," *Electron. Lett.*, vol. 49, no. 9, Apr. 2013, DOI: 10.1049/el.2013.0840.