All-Optical Updating of Subcarrier Encoded Packet Headers with Simultaneous Wavelength Conversion of Baseband Payload in Semiconductor Optical Amplifiers

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***Abstract*—All-optical updating of subcarrier multiplexed headers and the simultaneous wavelength conversion of baseband payload is demonstrated. Updating is achieved by utilizing the low-pass frequency response of wavelength conversion via cross gain modulation in semiconductor optical amplifiers to suppress the original subcarrier multiplexed header while efficiently converting the baseband payload. A new header is then inserted by optically modulating the output of the wavelength converter with the new subcarrier encoded data. Updating of a pseudorandom 100 Mb/s header coded on a 16.5-GHz microwave subcarrier is achieved with wavelength conversion of a 2.5-Gb/s pseudorandom baseband payload. Crosstalk measurements are presented to determine cascadability of this technique and indicate that subcarrier suppression of 16.9 dBe followed by 20.2-dBe remodulation overcomes degradation due to residual original subcarrier and remodulation of the baseband payload. A key feature of this technique is the preservation of all-optical baseband payload transparency up to the header subcarrier frequency.**

***Index Terms*— Optical switching, subcarrier multiplexing, wavelength conversion.**

I. Introduction

PACKET switching with subcarrier multiplexed (SCM) headers in wavelength division multiplexed (WDM) optical networks [1]–[3] has received increasing attention due to the reduced timing constraints for header extraction compared to serial techniques, header detection using a small portion of the optical signal, and the use of conventional microwave and digital electronics for header processing. Certain packet switched network architectures require that headers be updated or modified during the routing process (e.g., asynchronous transfer mode (ATM) switching [4] and deflection routing [5]).

For all-optical packet switching networks, the process of updating SCM headers in a manner that preserves the optical transparency of the baseband payload is necessary. This has previously been accomplished by transmitting the payload and header on separate wavelengths, wavelength demultiplexing the header for optoelectronic conversion, electronic processing, and retransmission on the header wavelength [5], [6]. This approach had drawbacks in that fiber dispersion separates the header and payload as packets traverse the network. Since SCM headers are more closely spaced in frequency to the baseband, dispersion is not as much an issue. In principle, optical demultiplexing can be applied to remove optical SCM headers using narrow-band optical filtering. This approach, however, would be extremely sensitive to wavelength drift. Hence, previous practical SCM header replacement techniques have been limited to optoelectronic conversion of the entire packet followed by electronic filtering, remodulation, and retransmission on a new laser.

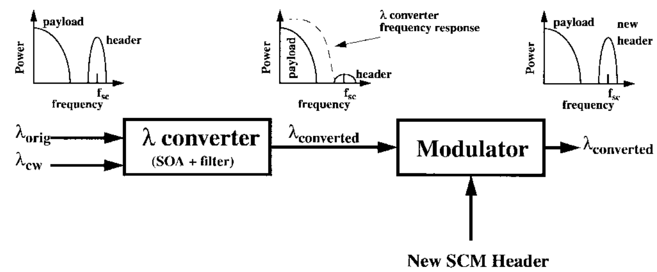

Fig. 1. Block diagram of all-optical SCM encoded packet header updating technique. The wavelength converter simultaneously converts the baseband payload signal and suppresses the SCM header signal. A new header is then modulated onto the converted optical signal.

In this letter, we describe and demonstrate a new all-optical technique for SCM header updating (removal and reinsertion) that preserves the transparency of the baseband payload up to the subcarrier frequency and provides for wavelength conversion of the packet. Our technique involves a two-stage process: First, simultaneous SCM header suppression and wavelength conversion of the baseband payload is achieved due to the low-pass frequency response of cross-gain modulation (XGM) in semiconductor optical amplifiers (SOA's) [7], [8] and then header replacement is performed by optically remodulating the wavelength converted signal with a new header at the original subcarrier frequency. We also address the important issue of cascadability by measuring bit-error rate (BER) as a function of crosstalk due to unsuppressed SCM header and intermodulation distortion (IMD) due to wavelength converted baseband that is multiplexed to the header channel during remodulation.

II. Description of Technique

A block diagram of the technique is illustrated in Fig. 1. An optical SCM packet is generated by amplitude modulation of a microwave subcarrier with a digital header that is combined

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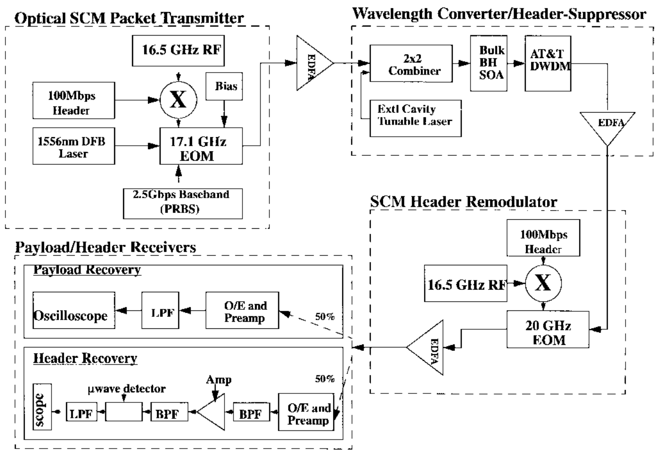
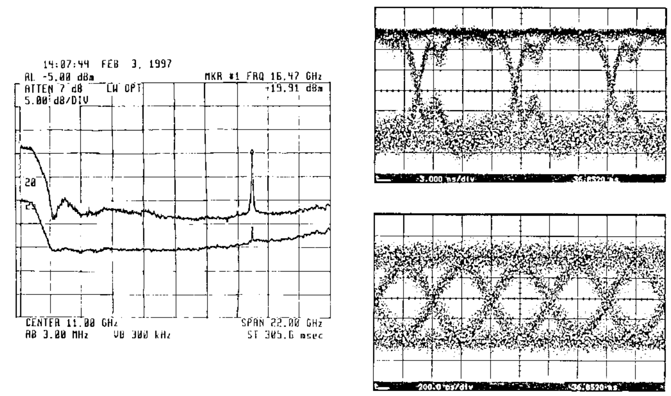


Fig. 2. Experimental setup illustrating the four subsystems: 1) The optical SCM packet transmitter; 2) the SOA wavelength-converter/header-suppressor; 3) the SCM remodulator; and 4) the payload/header receivers.



(a) (b)

Fig. 3. Experimental results. (a) Power spectrum of transmitted (upper trace) and wavelength converted (lower trace) signals. (b) Recovered 100 Mb/s, PRBS updated header (upper trace) and 2.5 Gb/s, PRBS wavelength converted baseband payload (lower trace) signals.

with a digital baseband payload onto an optical carrier $\lambda_{\rm orig}$ using an optoelectronic technique [3]. The electrical power spectrum of the transmitter output is illustrated in the left-hand inset in Fig. 1. The optical SCM packet at $\lambda_{\rm orig}$ is combined with a continuous-wave (CW) optical signal at $\lambda_{\rm conv}$ at the input to an SOA. Wavelength conversion is achieved by transfering information from $\lambda_{\rm orig}$ to $\lambda_{\rm conv}$ through XGM in the SOA [7]. The small-signal frequency response of XGM wavelength conversion in SOA's behaves as a single-pole low-pass filter and can be expressed as [7]

$$H_{\rm lpf}(f) = \frac{C}{1 + j2\pi\tau_e f} \tag{1}$$

where τ_e is the effective carrier lifetime and C is constant for a given SOA and input signal.

If the corner frequency of the low-pass wavelength conversion response $H_{\rm lpf}(f)$ is located at a higher frequency than the bandwidth of the baseband payload but far enough below the subcarrier channel, the SOA will efficiently convert the baseband payload to the new wavelength while suppressing the SCM header signal as shown in the center electrical power spectrum in Fig. 1. Sufficient suppression of the original subcarrier header then allows optical insertion of a new SCM header using an optical modulator.

III. Experiment and Results

All-optical SCM header replacement with baseband payload wavelength conversion was successfully demonstrated using the experimental setup shown in Fig. 2. The four experimental subsystems are: 1) the optical SCM packet transmitter; 2) the SOA wavelength-converter/header-suppressor; 3) the SCM header remodulator; and 4) the payload/header receivers. The original SCM header was generated by amplitude modulating a 16.5-GHz microwave subcarrier with a 100 Mb/s, nonreturn-to-zero (NRZ), $2^{15}-1$ pseudorandom bit sequence (PRBS). The SCM header and a 2.5-Gb/s PRBS baseband payload were used to separately drive the two arms of a Mach–Zehnder integrated-optic modulator to impress the combined packet onto the output of a 1556-nm DFB laser. An erbium-doped fiber amplifier (EDFA) was used to boost the packet transmitter output power. The optical SCM packets were combined with a 1541.4-nm CW signal into a bulk buried heterostructure SOA followed by an optical filter, realizing 14.6-nm down-conversion.

In Fig. 3(a), the electrical power spectrum of the optical SCM packet at the SOA input (upper trace) is compared to the electrical power spectrum of the wavelength converted output (lower trace). The header is suppressed by 30.18 dBe compared to the original header while the baseband experiences a loss of about 20 dBe due to reduced modulation depth after wavelength conversion. The SCM header is suppressed by 10 dBe relative to the baseband payload due to the <3 GHz 3-dB corner frequency of the low-pass frequency response of the XGM wavelength converter. Remodulation of a new SCM header onto the wavelength converted signal is acheived using an external modulator driven by amplitude modulation of a 16.5 GHz microwave subcarrier with a new 100 Mb/s, 2^7-1 PRBS data stream and driving an integrated optic modulator. The output of the remodulator is boosted using an optical amplifier.

The received updated SCM header and converted baseband payload eye diagrams are shown in the upper and lower traces of Fig. 3(b), respectively. The SCM header is recovered using a microwave square-law detector following photodetection and the baseband payload is direct detected. The header bits are inverted due to the microwave detector while the baseband payload is inverted as a result of the XGM wavelength conversion process. We measured a BER for the recovered header signal at 1×10^{-11} and for the payload signal at 2.2 $\times$ 10^{-12}.

IV. Cascadability

Cascadability is critically important in photonic switched networks where header replacement is performed on the same packet at multiple nodes. Degradation of the updated header will occur due to two primary mechanisms: 1) crosstalk due to the incomplete suppression of the original SCM header and 2) IMD due to partial upconversion of the baseband payload into the header passband during remodulation. The electrical crosstalk, as we measured it, can be defined as the ratio of the bandpass filtered (BPF) residual original subcarrier signal

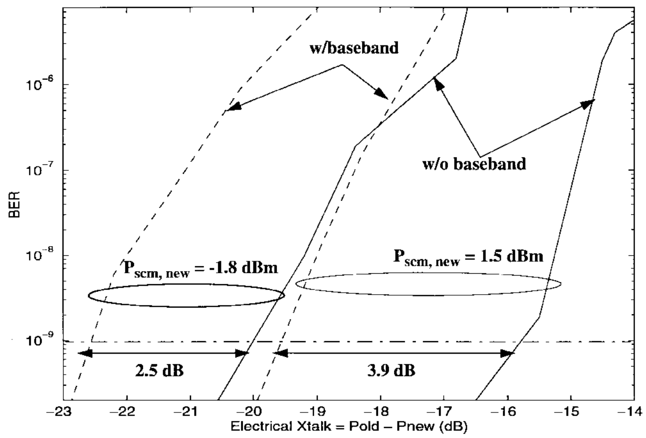


Fig. 4. BER as a function of crosstalk between original (old) and updated (new) SCM signals. BER of $<10^{-9}$ is indicated by the dot–dash line. Solid curves are of measurements made in the absence of baseband payload; dashed curves are of measurements made with the baseband payload present.

power to the new subcarrier signal power in

$$Xtalk = \frac{\int_{f_{SC}-B/2}^{f_{SC}+B/2} |H_{lpf}(f)|^2 P_{SC,orig} S_{hdr,orig}(f-f_{SC})|BP(f)|^2\, df}{\int_{f_{SC}-B/2}^{f_{SC}+B/2} P_{SC,new} S_{hdr,new}(f-f_{SC})|BP(f)|^2\, df} \tag{2}$$

where $S_{hdr,orig}(f-f_{SC})$ and $S_{hdr,new}(f-f_{SC})$ are the power spectra of the original and new SCM headers, respectively, f_{SC} is the subcarrier frequency, $BP(f)$ is the complex electronic BPF function for recovery of the header after photodetection and B is the passband of BPF. $P_{SC,orig}$ and $P_{SC,new}$ are the respective powers of the original and new subcarriers.

Degradation of the recovered header signal-to-noise ratio (SNR) due to subcarrier crosstalk is determined by measuring the received subcarrier power of the residual original header and the new header, each in the absence of the other. The ratio of the received original subcarrier power to the received new subcarrier power is the measured crosstalk. BER's are measured with both SCM signals present and in the presence and absence of the baseband payload signal. Fig. 4 shows that for an updated SCM header with −1.8 dBm subcarrier power the crosstalk must be < -20 dBe in order to achieve BER $< 10^{-9}$ in the absence of baseband payload. Increasing the subcarrier power to 1.5 dBm increases the tolerable crosstalk level by 4.3 dB to −15.9 dBe.

Degradation of the recovered header SNR also occurs due to IMD from upconverted baseband payload after remodulation passing through the header receiver bandpass filter. The IMD can be defined as the ratio of the BPF, upconverted payload power to the updated subcarrier power:

$$I_{IMD} = \frac{\int_{f_{SC}-B/2}^{f_{SC}+B/2} A(P_{SC,new}) S_{BB}(f-f_{SC})|BP(f)|^2\, df}{\int_{f_{SC}-B/2}^{f_{SC}+B/2} P_{SC,new} S_{hdr,new}(f-f_{SC}|BP(f)|^2\, df} \tag{3}$$

where $S_{BB}(f-f_{SC})$ is the power spectrum of the upconverted baseband payload signal. $A(P_{SC,new})$ is the power in the upconverted signal and is a nonlinear function of the power of the new subcarrier; its form will be addressed in future work.

Fig. 4 shows that for a −1.8-dBm updated subcarrier a 2.5-dB penalty is incurred due to the presence of the baseband payload, reducing the crosstalk level for BER $= 10^{-9}$ or less to −22.7 dBe; the penalty is about 3.9 dB when a 1.5-dBm updated subcarrier is used, decreasing the tolerable crosstalk level to about −19.8 dBe. This increased penalty is due to stronger modulation of the baseband payload by the stronger updated SCM header signal resulting in a greater amount of intermodulation interference. Increasing the subcarrier power further would likely lead to even greater penalty and a reduction in the tolerable crosstalk level.

V. Conclusion and Summary

A new technique for all-optical SCM header updating in WDM packet networks has been demonstrated. Experimental results show that simultaneous header replacement and baseband payload wavelength conversion can be achieved through XGM in a SOA. Crosstalk of −19.8 dBe permitted BER $< 10^{-9}$ for the header and baseband signals after modulation of the converted optical signal by a new header at the original subcarrier frequency. This crosstalk includes a penalty incurred due to IMD by upconverted baseband payload. This penalty increased 1.4 dB (from 2.5 to 3.9 dB) when the power of the new subcarrier was increased from −1.8 to 1.5 dBm suggesting that further increases in the new subcarrier power results in higher penalties and a reduction in the tolerable crosstalk level. A detailed time-domain model of signal propagation through the wavelength converter and header remodulator is now being developed to enhance our analysis of $A(P_{SC,new})$ as well as the XGM process. Our technique preserves the baseband payload data rate and format transparency up to the subcarrier frequency and is more practical, less complicated, and less costly to implement than previous header updating techniques.

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