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All-Optical Subcarrier Labeling Based on the Carrier Suppression of the Payload

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***Abstract*—We report on a new approach to all-optical subcarrier labeling based on sideband generation through carrier-suppression of the payload. The experimental transmission over 50-km standard fiber of a 10-Gb/s payload data multiplexed with a synchronized 1.25-Gb/s subcarrier label is carried out with less than 1-dB receiver power penalty, clearly demonstrating the feasibility of this sideband optical labeling scheme. The requirements to the modulation index and dc bias along with the limitation of the input extinction ratio are discussed.**

***Index Terms*—All-optical labeling, carrier suppression, optical packet switching, subcarrier multiplexing.**

I. Introduction

All-optical packet switching using in-band optical label has great potential in future Internet protocol (IP) over wavelength-division-multiplexing networks for removing the bottleneck of IP packet routing and forwarding as individual fiber link rates approach terabits per second, and also for achieving high spectra efficiency [1]. Several techniques for optical labeling have been reported by using subcarrier multiplexed addressing [2]–[4] orthogonal modulation format for the intensity-modulated payload [5], [6]. The subcarrier multiplexing technique requires a radio frequency (RF) mixer [2]–[4], and in some proposals coherent detection is necessary [4]. In the orthogonal modulation scheme, crosstalk between the intensity modulated payload and the phase modulated label occurs during transmission [5], [6].

In this letter, we report a novel scheme of optical subcarrier label generation. The synchronized optical label is modulated onto the sidebands that are produced by suppressing the carrier of the payload. The sideband label and the payload can be combined and separated from each other simply by using a directional coupler and an optical filter, respectively. The first experimental transmission over 50-km standard fiber (SMF) of this all-optically labeled packet with optical sideband addressing is successfully demonstrated. The transmission penalty of the payload and label is found to be below 1 dB, clearly demonstrating the feasibility of this sideband optical labeling scheme.

The tolerance of the modulation index and the dc bias required by the sideband generation as well as the limitation of the input extinction ratio are all discussed.

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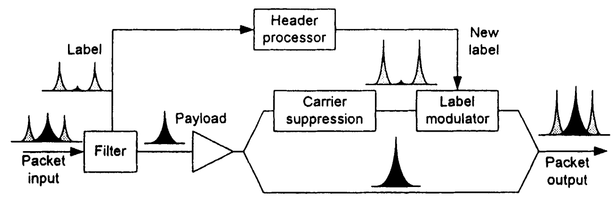

Fig. 1. Schematics of optical sideband labeling.

II. Principle

The basic concept of optical label swapping of the sideband labeled packet is illustrated in Fig. 1. The incoming label is separated from the payload by an optical filter and is injected into the label processing module. The pure payload is amplified and split into two parts by a 3-dB coupler. At the first tributary, the payload carrier is suppressed so that two sidebands are generated, the new label is then modulated onto the sidebands and combined with the payload in the second branch by another 3-dB coupler. Thus, the new label is added to the payload and the label swapping process is accomplished.

The advantages of this scheme include that the modulation and detection of the payload and label can be achieved independently, and that no additional tunable lasers are necessary at the label-swapping node. Because the sidebands are directly generated from the payload carrier, the possibility of overlap between payload and label when using an external laser is totally prevented.

The carrier suppression technique is realized by using two RF signals with π-phase shift to drive a Mach–Zehnder modulator (MZM) biased at its null point [7]. The electrical field of the intensity-modulated signal with limited extinction ratio can be expressed as

$$E_{\rm in}(t)=\sqrt{\varepsilon+\sum_{i=-\infty}^{+\infty}(1-\varepsilon)q_i\cdot g(t-iT)}\cdot E_0e^{j\omega_{\rm c}t}=E_0'\cdot e^{j\omega_{\rm c}t}. \tag{1}$$

Here, q_i is the data sequence, T the bit period, $g(t)$ the pulse shape, and $\omega_{\rm c}$ the angular carrier frequency. The extinction of payload is $-10\log(\varepsilon)$. The output field of the MZM can be described as [8]

$$E_{\rm out}(t)=\frac{E_{\rm in}(t)}{2}\left(e^{j\phi_1(t)}+e^{j\phi_2(t)}\right) \tag{2}$$

$$\phi_1(t)=\frac{\pi V_{\rm 1m}}{V_\pi}\cos(\omega_m t+\pi)+\frac{\pi V_{\rm bias}}{V_\pi} \tag{3}$$

$$\phi_2(t)=\frac{\pi V_{\rm 1m}}{V_\pi}\cos\omega_m t. \tag{4}$$

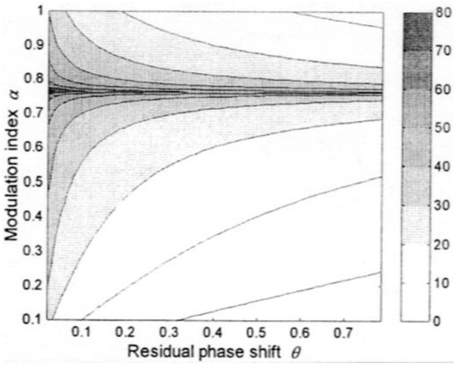

Fig. 2. Contour plot of carrier suppression ratio as a function of residual phase shift and modulation index.

Here, ϕ_1 and ϕ_2 represent the phases of the two modulator arms, ϕ_1 is biased with the dc voltage $V_{\rm bias}$, $V_{\rm 1m}$ and $V_{\rm 2m}$ are the amplitudes of the RF signals and are assumed to be the same. V_π is the voltage that is required in the MZM for a π-phase shift. If we define the modulation index $\alpha = V_{\rm m}/V_\pi$, the residual phase $\theta = (V_{\rm bias}/V_\pi) - \pi$ which indicates the disparity from the null point of the MZM), the output field can be derived as

$$\begin{aligned} E_{\rm out}(t) = & E_0' e^{j\omega_c t} \cdot e^{j\frac{\pi+\theta}{2}} \\ & \cdot \Bigg\{ 2\cos\frac{\theta}{2} \cdot \sum_{k=0}^{\infty} (-1)^k J_{2k+1} \\ & \times (\alpha\pi) \cos\left[(2k+1)\omega_m t\right] + \sin\frac{\theta}{2} \\ & \times \left[J_0(\alpha\pi) + 2\sum_{k=1}^{\infty} (-1)^k J_{2k}(\alpha\pi) \cos(2k\omega_m t) \right] \Bigg\} \end{aligned} \tag{5}$$

where J_n is the Bessel function of first kind and order n.

The suppression ratio between the first-order harmonic and the carrier is then given by

$$S_R = 20 \log \left| \frac{\cos\frac{\theta}{2} \cdot J_1(\alpha\pi)}{\sin\frac{\theta}{2} \cdot J_0(\alpha\pi)} \right|. \tag{6}$$

The contour plot of the suppression ratio as a function of the modulation index and residual phase shift is shown in Fig. 2. An optimum modulation index of 0.765 is found which is totally independent of residual phase shift. Therefore, even if the MZM is not working at null point, a large suppression ratio of more than 80 dB can still be achieved by changing the RF voltage.

The eye opening of the label as a function of the extinction ratio of the payload is depicted in Fig. 3. Clearly, the eye opening is decreased when increasing the payload extinction ratio. Therefore, it should be envisaged that a limited extinction ratio for the payload is required in order to detect the label.

III. Experiment

The experimental setup is shown in Fig. 4. A wavelength tunable external cavity laser working at 1555.2 nm is externally modulated by an MZM at 10 Gb/s. As we have discussed before, an input extinction ratio of 4 dB is used for the payload. The carrier suppression occurs in another push–pull type MZM driven

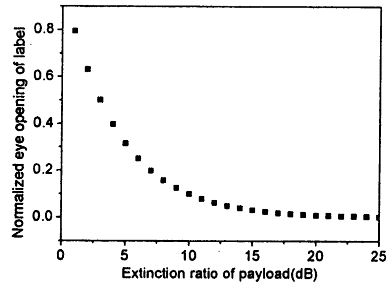

Fig. 3. Eye opening of label normalized by maximum optical power versus extinction ratio of payload.

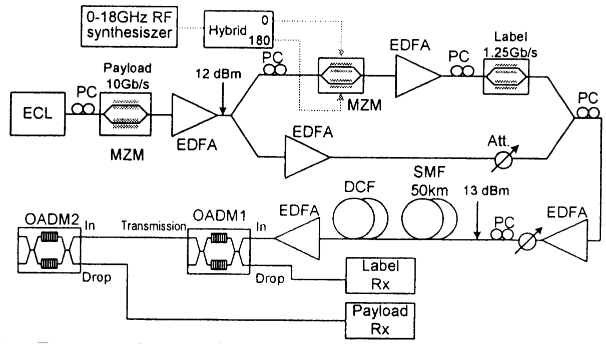

Fig. 4. Experimental setup.

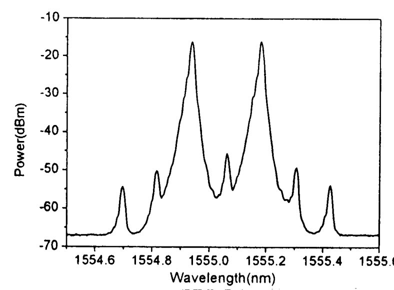

Fig. 5. Optical spectrum of carrier suppressed intensity modulated payload at 10 Gb/s.

by a sinusoidal clock signal at 15 GHz. By changing the polarization state of the polarization controller before the push–pull MZM and the input RF voltage, a suppression ratio of up to 30 dB can be achieved, as shown in Fig. 5. Two sidebands with 30-GHz spacing are generated and the 1.25-Gb/s label is then modulated onto the sidebands. The payload is then combined with the sideband label via a 3-dB coupler, thus making the optically labeled packet ready for transmission. The transmission span consists of 50-km SMF followed by 8.6-km dispersion-compensating fiber. A variable attenuator is inserted before the transmission fiber link to get optimum span input power.

At the receiver, two fiber-Bragg-grating-based OADMs with carefully selected rising edges are deployed to extract the sideband label and the payload, respectively. The optical spectra of the payload with sideband label and the reflection of the two OADMs are shown in the inset of the Fig. 6. Because of the sharp edges of the OADMs, the extracted label and payload have a signal-to-noise ratio of about 20 dB. It can be expected that a larger signal-to-noise ratio can be obtained if a narrow notch filter is used for the payload and label separation.

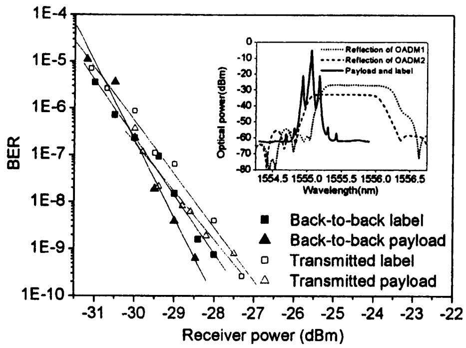

Fig. 6. Measured BER performance for back-to-back and after 50-km transmission over SMF. Inset figure shows optical spectrum of payload combined with sideband label, and reflection spectra of OADM1 and OADM2.

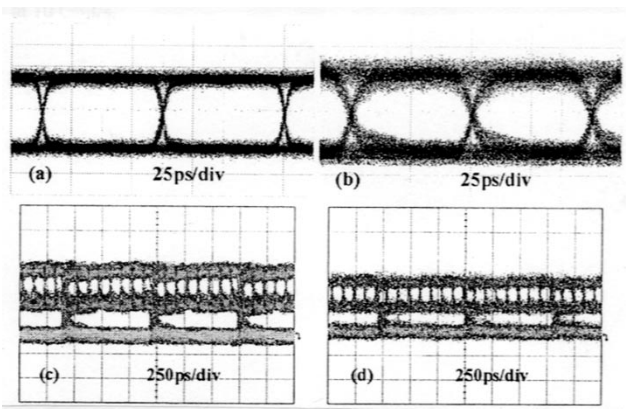

Fig. 7. Measured eye diagrams of (a) back-to-back payload, (b) payload after 50-km transmission, (c) back-to-back label, and (d) label after 50-km transmission.

The eye diagrams of the original data and the transmitted signal are shown in Fig. 7. Due to the intrinsic amplitude fluctuation of the intensity modulated payload, the received label eye diagram has a multilevel structure. The microstructure of the 'mark' level reveals the information at 10 Gb/s. Because the payload and the label are synchronized with each other, every eye of the label has eight small eyes. However, this does not mean that the receiver of the label should be modified; both the payload and label can be detected directly by a conventional photodiode.

The measured bit-error rate (BER) performance of the payload and label for back-to-back and after 50-km transmission are shown in Fig. 6. Error-free transmission of both payload and label can be achieved simultaneously. After transmission, the label and payload show a small power penalty below 1 dB.

Cascadability is critically important in optically switched networks where the label replacement is performed on the same packet at multiple nodes [9]. In our scheme, degradation of the updated label will occur due to the crosstalk caused by the incomplete suppression of the original sideband label. Furthermore, the finite suppression ratio of the carrier will become a source of payload deterioration, and the incurred crosstalk can accumulate after several label swappings. It should be noted that cascadability in this scheme is dependent on the performance of both the payload and label, and this will be investigated in our future work.

IV. Conclusion

We have reported a novel scheme of all-optical subcarrier labeling based on carrier suppression of the payload. Error-free transmission over 50-km SMF with less than 1-dB power penalty has been demonstrated for both payload and label of the all-optically labeled packet using optical sideband labeling technique.

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