Novel Self-Synchronization Scheme for High-Speed Packet TDM Networks

T. J. Xia, Y.-H. Kao, Y. Liang, J. W. Lou, K. H. Ahn, O. Boyraz, G. A. Nowak, A. A. Said, and M. N. Islam

***Abstract*—We demonstrate a novel self-synchronization scheme for high-speed packet time-division-mulitplexed (TDM) networks using a fast saturated, but slowly recovered gain (or loss) combined with intensity discrimination. The marker pulse used in this self-synchronization scheme is the same as other pulses in the packets. In particular, we use a semiconductor optical amplifier (SOA) as the fast saturated but slowly recovered gain element, and an unbalanced nonlinear optical loop mirror or a dispersion-shifted fiber/optical filter combination as an intensity discriminator. The contrast ratio of the first pulse to the remaining pulses of a 100-Gb/s packet, "10111000" is $>$3 dB at the output of the SOA and $>$20 dB at the outputs of both intensity discriminators.**

***Index Terms*—Optical fiber communication, optical saturation, optical signal processing, synchronization, packet switching, ultrafast optics.**

SELF-SYNCHRONIZATION is an important issue in high-speed packet networks [1]–[4]. With self-synchronization, instead of performing clock recovery, a local access node on the network selects a single pulse from an incoming data packet. This single pulse can be used as a seed pulse to generate various local bit patterns, such as local clocks or local addresses. Because the extracted seed pulse is automatically synchronized to the incoming packet, these local bit patterns can be aligned with the incoming packet with high accuracy. This seed pulse is only used for the packet that contains it, therefore, this synchronization scheme is tolerant to timing jitter between packets. We demonstrate a novel self-synchronization scheme that uses a semiconductor optical amplifier (SOA) and one of two intensity discriminators for packets with a generic pulse frame, i.e. the marker pulse is identical to the other pulses in the packet. In this scheme, the first pulse of a packet is transmitted through the SOA with a $>$3-dB intensity contrast ratio over the other pulses in the packet due to fast gain saturation. The intensity ratio is further enhanced to $>$20 dB when the packet passes through intensity discriminators.

Previous demonstrations of self-synchronization schemes have involved using marker pulses which are different from other pulses in the packets. Shimazu and Tsukada use marker pulses of different wavelength, which can be separated by a wavelength filter at a receiver [1]. Glesk *et al.* use a marker pulse whose polarization is orthogonal to that of the remaining pulses in the packet and can be selected with a polarizer [2]. The marker pulse used by Cotter *et al.* is placed ahead of the packet with a separation of one and a half bit-period. This pulse is extracted by an AND gate with one and a half bit period shift between the control and signal pulse trains [3]. In addition, Deng *et al.* demonstrated a self-synchronization scheme by using a marker pulse five times stronger than other pulses in the packet. The marker pulse is distinguished by a terahertz optical asymmetric demultiplexer [4]. Using these markers requires that the data packet have a special pulse, which complicates the generation and transmission of the packets. Marker pulses of different wavelength may lose their timing relation with other pulses in the packet due to the dispersion in fibers. Marker pulses with different polarization or different intensity may lose their uniqueness after propagating a long distance. For marker pulses with different bit-period, packet generation becomes complicated and any jitter between pulses could cause trouble in extraction of the marker pulse.

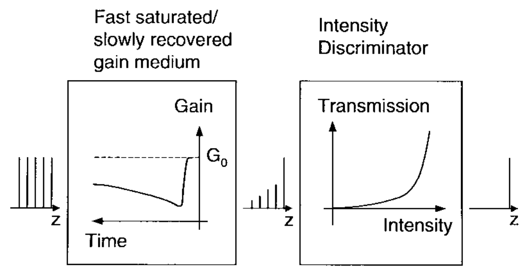

Fig. 1. Schematic diagram of the self-synchronization scheme. It contains two elements: Fast saturated/slowly recovered gain medium and intensity discriminator. G_0—unsaturated gain.

We design a new approach to extract a single pulse, i.e., the first pulse, from packets. Here, we can consider the first pulse as a marker. Fig. 1 shows a schematic diagram for the design. First, a transmission function with a fast saturated/slowly recovered gain medium is imposed across the packet to create higher intensity for the first pulse in the packet. Then, the remaining pulses of the packet are removed with an intensity discriminator. This design does not require the marker pulse to be different from the other pulses. The only requirement is that the guard time between packets be longer than the recovery time of the gain element. A fast saturated/slowly recovered loss medium can be used for the same purpose.

We choose an SOA to perform the fast saturated/slowly recovered transmission function. SOA's have very fast gain

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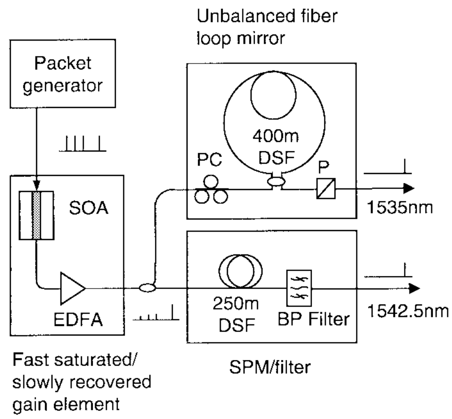

Fig. 2. Experimental setup for self-synchronization. An SOA is used as the fast saturated/slowly recovered gain element. Two types of intensity discriminators, unbalanced fiber loop mirror and SPM/filter, are used. PC: Polarization controller. P: Polarizer. DSF: Dispersion-shifted fiber. SPM: Self-phase modulation. BP: Bandpass. EDFA: Erbium-doped fiber amplifier.

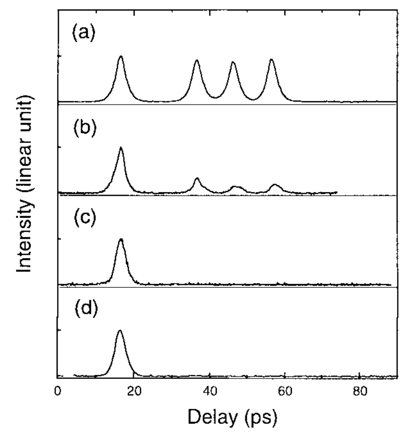

Fig. 3. Cross-correlation results of the self-synchronization scheme. (a) Input data packet. (b) Output data packet from the SOA. (c) Extracted single pulse from the unbalanced loop mirror intensity discriminator. (d) Extracted single pulse from the SPM/filter intensity discriminator.

saturation when excited with short optical pulses and the saturation can occur during one pulse width for pulses of several picoseconds [5]. The saturated gain of the SOA, however, has a relatively long recovery time, which ranges from 0.2 to 1 ns depending on different SOA's [6]. By properly setting the input power of the optical pulses and bias current of the SOA, only the first pulse in the packet experiences an unsaturated gain, while the remaining pulses experience a gain saturated by the first pulse. The gain difference causes the first pulse of a transmitted packet to have a greater intensity than the remaining pulses. An intensity discriminator then selects the first pulse and suppresses the rest, resulting in a single pulse being extracted from the packet.

We design two types of intensity discriminators. One is an unbalanced nonlinear optical loop mirror (NOLM) with a polarizer, and the other employs spectral broadening due to self-phase modulation (SPM) in fiber combined with an optical filter. For the intensity discriminator using the unbalanced NOLM, the coupler in the loop has an uneven beam splitting ratio, and the clockwise and counterclockwise beams in the loop experience different nonlinear phase shifts. This phase shift difference is a function of input intensity of the pulses. The NOLM can be adjusted so that it has a higher transmission for the high intensity pulse than that for low intensity pulses. Additionally, since nonlinear polarization rotation induced in the fiber of the loop mirror is also intensity dependent, a polarizer at the output of the loop mirror increases the contrast ratio. For the SPM/filter intensity discriminator, a fiber with a zero-dispersion wavelength λ_0 very close to the working wavelength is used to obtain sufficient spectral broadening. The width of the broadened spectrum of a pulse has a nonlinear dependence on input intensity. We set a band pass filter at a wavelength slightly away from the input wavelength, so that only the pulse with enough intensity can pass this filter, and all others will be eliminated.

Fig. 2 shows the experimental setup of our self-synchronization design. A data packet (the shortest duration between pulses is 10 ps, i.e., 100 Gb/s) is generated by a passively modelocked fiber laser ($\lambda = 1535$ nm, $\tau = 1.5$ ps) followed by a fiber encoder comprised of couplers and delay lines. The data packet is sent to an SOA to obtain a pulse train with a strong first pulse. The output from the SOA is sent to one of the intensity discriminators via an erbium-doped fiber amplifier (EDFA) to compensate for the 1-dB net insertion loss of the SOA and to enhance the energy in the pulses. The energy of the first pulse is 15 pJ at the output of the EDFA. For the unbalanced NOLM intensity discriminator, we use a 40/60 coupler, and a dispersion-shifted fiber (DSF) ($L = 400$ m with $\lambda_0 = 1493$ nm). For the SPM/filter intensity discriminator, we use a 250-m DSF ($\lambda_0 = 1539$ nm), and tunable bandpass filter (central wavelength is tuned to 1542.5 nm with 2.3-nm bandwidth). The pulses in the packet are analyzed with a cross-correlator, an autocorrelator, and a spectrum analyzer at the outputs of the SOA and intensity discriminators.

Fig. 3 shows the cross-correlation at different stages of the self-synchronization unit. Using an input energy of 2 pJ/pulse to saturate the SOA at a current of 50 mA, we obtain an intensity contrast ratio of more than 3 dB between the first pulse and the remaining ones in the packet for a uniform input pulse train [Fig. 3(b)]. The resultant 3-dB contrast ratio is not sensitive to input pulse energy (when input power varies $\pm 20\%$). This intensity contrast is further enhanced to >20 dB after the unbalanced NOLM [Fig. 3(c)] or the SPM/filter [Fig. 3(d)] intensity discriminator. The net insertion loss of the SOA is 1 dB for the first pulse. With the EDFA between the SOA and the intensity discriminators, the overall insertion gain for the first pulse of the packet is 6.5 dB using the NOLM discriminator and 3.5 dB using the SPM/filter discriminator.

The autocorrelation and optical spectra of these extracted single pulses at the output of the self-synchronization setup are illustrated in Fig. 4 and compared to those of the input pulses. It is important to maintain the pulse quality with insertion of the self-synchronization unit as the extracted pulse will be used as a seed pulse to generate local bit patterns. A slight frequency shift can be seen for the case using the unbalanced loop mirror as the intensity discriminator. It is a typical phenomena related to gain saturation in a SOA device [5]. The time-bandwidth-

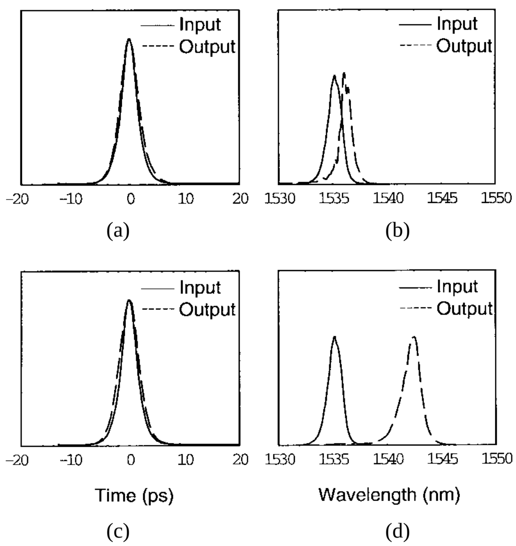

Fig. 4. Auto-correlation and spectra of the extracted pulse from (a)–(b) the unbalanced loop mirror intensity discriminator and (c)–(d) the SPM/filter intensity discriminator. All y-axes are in linear scales.

product of the extracted pulse is 0.34 using the unbalanced NOLM intensity discriminator [Fig. 4(a)–(b)] and 0.48 using the SPM/filter intensity discriminator [Fig. 4(c)–(d)].

The two types of intensity discriminators fit different applications. The extracted pulse emerging from the unbalanced NOLM intensity discriminator has nearly the same wavelength as that of the input packet. This pulse is a suitable source for generating bit patterns for devices requiring inputs of similar wavelengths, such as in cascaded logic operations [7]. The extracted pulse emerging from the SPM/filter intensity discriminator has a shifted wavelength from that of the output packet. A device requiring inputs with two wavelengths, such as the all-optical demultiplexer [8], can use the extracted pulse as a source.

This self-synchronization does place some restrictions on the packet frames. It requires a time guard band between packets to be longer than the SOA recovery time. A long series of zeros followed by ones in the packet may also be misinterpreted as the beginning of a new packet because of the SOA gain recovery. Adding an extra gate that is turned off after receiving the first extracted pulse and turned on after the fixed packet duration is a possible solution. Such a gate would also prevent most of the pulses in the packet from going to the self-synchronization unit, thereby guaranteeing that the first pulse of the subsequent packet obtains maximum gain.

In summary, we demonstrate a self-synchronization technique that extracts the first pulse of a 100-Gb/s packet, “10111000,” with contrast ratio of $>$20 dB by using the fast saturated/slowly recovered gain in an SOA and two types of intensity discriminators. The extracted pulse experiences a net gain of 6.5 dB at the original wavelength using the NOLM discriminator and a net gain of 3.5 dB at a different wavelength using the SPM/filter discriminator. This synchronization scheme can be used for high-speed packet networks or ultrafast optical sampling.

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