Optimization of a Switching Node for Optical Multistage Interconnection Networks

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***Abstract*—In this letter, we demonstrate a 2×2 switching node optimized for optical multistage interconnection networks. The optical packet-switched node is improved by making use of comparators with dual-threshold action to regenerate the routing header signal. The switching node is shown to correctly route packets with the presence of glitches in the header information. We employ a hybrid integrated semiconductor optical amplifier in the switching node that reduces packet guard times enabling a 67% increase in the number of stages for large-scale multistage networks.**

***Index Terms*—Integrated optoelectronic devices, optical interconnects, optical packet switching (OPS), semiconductor optical amplifier (SOA).**

I. Introduction

OPTICAL packet switched (OPS) networks have been suggested as viable solutions for applications requiring high-capacity data routing with low communication latency [1]. One class of proposed OPS network topologies is multistage interconnection networks (MINs) comprised of 2×2 internal switching nodes [2]. MINs enable scaling the number of ports while using simple switching nodes and are often used in parallel and distributed high-performance computing systems [3]. Semiconductor optical amplifier (SOA) devices are perhaps the most commonly used switching elements in photonic node implementation for OPS networks [4]–[6]. In these SOA-based interconnection networks, the payload data is maintained in the optical domain while the optical packet headers are processed electronically and used to gate the SOA. Low noise figure SOA operating at a low gain setting enables node cascadability up to 50 SOA-based switching nodes [7], [8].

To reach their destination, optical packets propagate with time-of-flight latencies through a number of cascaded switching nodes arranged in a binary-tree fashion. At the physical layer, the maximum number of cascaded nodes ultimately determines the scalability of MINs where the number of stages is proportional to $\log_2(N)$ for an $N \times N$ interconnection network. In such a network, error-free propagation relies heavily on the mechanism by which the SOA switching device in the nodes is enabled. In electronically gated SOA devices, the optical transient response is affected by the interface between the optical-to-electrical (O/E) conversion feeding the routing pulse signal and the SOA's active region. At the node output, the optical packet envelope exhibits the same shape as the SOA optical step response. Hence, the routing effectiveness of the switching node directly impacts the network scalability.

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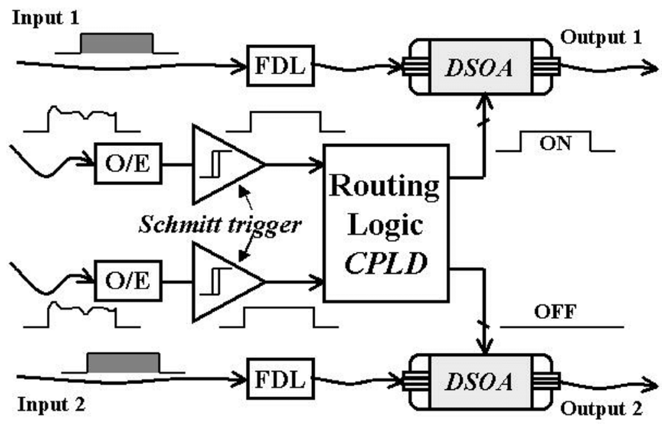

Fig. 1. Schematic of the multistage-optimized 2×2 switching node with Schmitt trigger comparators in the routing logic and fast switching DSOA, optical receivers (O/E), and fiber delay lines (FDL).

In this letter, we present two optimizations of an SOA-based switching node for scalable optical MINs. First, the node incorporates bistability using Schmitt trigger comparators within the routing decision logic for improved switching robustness and cascadability. To the best of our knowledge, this work represents the first use of a triggered receiver in an SOA-based switching node. Second, higher network scalability is achieved by reducing the guard times within the packet structure using a hybrid integrated digital SOA (DSOA) with a fast current driver. The switching time of the SOA is 40% faster than the state-of-the-art commercially available SOA devices. A similar approach has been suggested to enhance switching time, but the high-speed performance of the driver was limited by power consumption constraints [9], [10]. The optimized features presented in this letter are illustrated in Fig. 1. Preliminary measurements on these two designs have been reported separately in [11] and [12]. In this letter, we present a comprehensive report on the node performance optimizations enabling the network scalability of optical MINs.

II. SOA-Based Self-Routing Node

The broadband gain bandwidth of SOA-based nodes leverages the enormous capacity offered by wavelength-division multiplexing (WDM) and by the optical medium transparency to modulation formats and data rates. Within a multiple-wavelength optical packet structure for OPS network topologies, header and frame information can be encoded along specifically allocated wavelengths such as in [4]. The frame and header wavelengths are modulated with a constant binary value maintained for the packet duration. Packets self-route through the MIN by decoding the next most significant bit of the binary header address which is read at each stage by filtering the appropriate header wavelength. Two optical detectors convert the decoded header and frame information to electrical signals and are fed into a complex programmable logic device (CPLD). The generated decision signal controls one of the two SOA gates in the 2×2 switching node which are set to operate in the linear regime. The propagating packet and the electrical signal enabling the SOA are synchronized in time by appropriately delaying the packet using a specific length of optical fiber delay line. Guard times are inserted in the packet structure accounting for the finite transition times of the SOA devices.

There are several advantages to using this node structure implementation. The node routing is simplified and its latency is minimized by the parallel WDM header structure. Moreover, the optical power of the multiple-wavelength packet is maintained by using the SOA gain to compensate the node losses (e.g., connectors, couplers). Hence, network throughput and scalability are possible in MIN topologies [7], [8], but are dependent on the signal integrity of the routing decision.

III. Optimized Node for MINs

A. Header Regeneration Through Bistable Operation

The signal robustness of the routing decision will affect the node cascadability. In fact, fluctuation in the optical power of the signal is incident upon the DC-coupled optical detectors and ultimately feeds in the SOA affecting its optical response (Fig. 1). The use of Schmitt trigger comparators has been previously suggested to mitigate the effect of optical signal fluctuation and for signal regeneration at the receiver [13]. In this work, we present their use to alleviate the cascading effect of optical fluctuation on the payload data by regenerating the header signal of the packet being routed. From the dual threshold action (or hysteresis) of the comparators, a noisy header signal may have a voltage value below the high threshold value, but the output signal will not go to zero unless it falls below the low threshold value. The Schmitt trigger inputs of the CPLD are used with an input hysteresis threshold voltage at 80% (V_{T+}) and 20% (V_{T-}) of input high. When the input is between the two thresholds, the output retains its prior value for a more stable and robust node.

To demonstrate the efficiency of the bistable node, two glitches are induced in the optical signal incident on the detector [Fig. 2(a)]. For this investigation, a continuous-wave (CW) DFB laser emitting at 1555.75 nm is externally modulated with a 2.5-Gb/s pattern generator to represent one of the control signals. The average optical power is -15 dBm and the minimum average power sensitivity of the detectors is -26 dBm at 155 Mb/s. The artificial glitches are created by inserting a 400-ps-long digital zero at two instances in the data stream of consecutive ones. Without the Schmitt trigger comparators, the glitches propagate through the routing decision process and the driving signal to the DSOA exhibit the two glitches [Fig. 2(b)]. With only one input threshold in the routing logic, the digital signal switches back and forth from a low to high when the noisy incident signal is near its threshold value. In Fig. 2(c), a 2.5-Gb/s alternative bit sequence is used to demonstrate the effect on the payload of a routed packet by

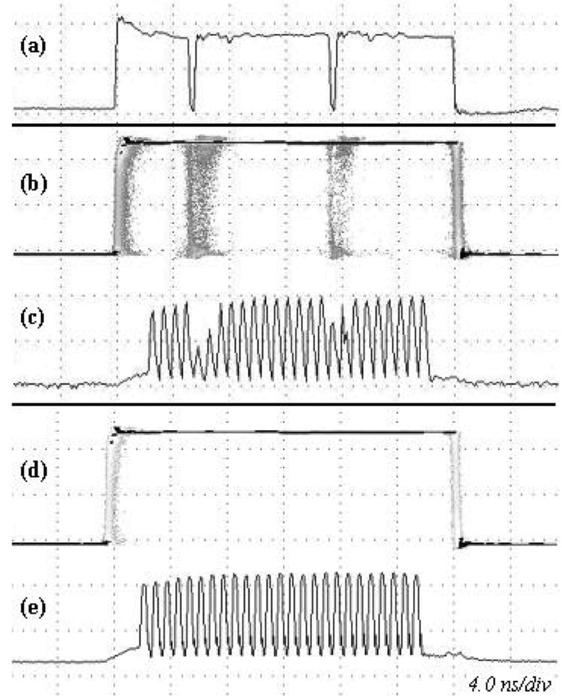

Fig. 2. Robust bistable switching operation. (a) Control signal with forced glitches. (b), (c) Disable comparators with routing decision fed to the DSOA with glitches and corresponding altered payload. (d), (e) Enabled comparators with routing decision and corresponding unaltered payload.

the falsely disabled DSOA. In Fig. 2(d), the Schmitt trigger comparators are enabled and the electrical routing decision signal exhibits no glitch. It should be noted that the bandwidth of the O/E conversion limits the depth of the glitch such that the signal level does not actually reach the high to low threshold voltage (V_{T-}). With the node bistable feature, the regenerated header signal properly enables the DSOA for the duration of the packet. The payload remains intact and is properly routed to subsequent nodes allowing node cascadability and network scalability [Fig. 2(e)]. To ensure efficient bistable operation within a DC-coupled O/E signal conversion, stable extinction ratio and average optical power values are required.

B. Fast DSOA Hybrid Integration

The node cascadability is essential in MINs, but is truly effective if the transition times of the switching elements are minimized. In systems limited by time-of-flight latencies, precision in timing affects the network scalability. For example, in the implemented MIN presented in [4], it has been shown that packets get truncated in average by 0.4 ns at each routing node due to the finite rise and fall times of the SOA which is approximately 0.9 ns [14].

In current commercial devices, the SOA devices packaging and the trace layout from the current driver to the SOA cathode limit the transition time response. The DSOA combines a high-speed current driver with an SOA device in a temperature controlled hybrid integration platform to alleviate this limitation. A commercial 10.7-Gb/s current driver die (MAX3934) with transition times of 25 ps and integrated load-matching network is bonded to the SOA active region. The DSOA resides in a

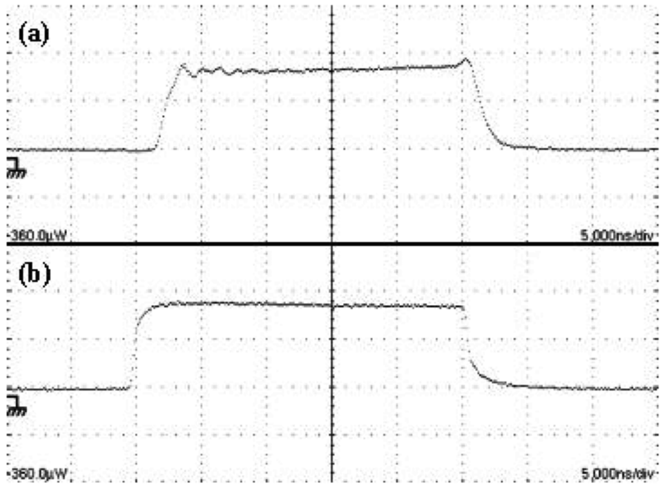

Fig. 3. Optical response of (a) commercial SOA device and (b) the DSOA device.

modified 28-pin butterfly package with two high-frequency subminiature B input connectors. The electrical pulse representing the routing decision generated by the CPLD is differentially fed to the DSOA as the packet is routed through the node. The forward current of the integrated current driver is externally tuned to a preset gain and a small DC current is provided to the DSOA to maintain the appropriate carrier density for a faster transition time.

The DSOA optical response was compared to a state-of-the-art commercial SOA from Kamelian (OPS-10-10-X-C-FA). Due to the bandwidth limitation of the O/E signal conversion, a 10-Gb/s capable pattern generator is programmed with a pulse representing a routing decision and fed directly to the DSOA device. In the case of the commercial SOA, the pulse is provided to an external current driver connected to the SOA device, with specified transition times of 40 ps. A CW DFB laser emitting at 1545 nm with an average optical power of -13 dBm is used to characterize the optical response of both devices. The DSOA exhibits an input saturation power of -2 dBm and a noise figure of 7 dB compared to 0 dBm and 6.5 dB for the commercial SOA, respectively. Both devices operate in the linear regime with their gain set to 5 dB.

As shown in Fig. 3, two significant improvements are achieved with the DSOA. First, the DSOA device exhibits much improved optical transient response with less overshoot and ripples compared to the SOA. The parasitic from the package leads are eliminated in the DSOA device and the interface is better matched mitigating possible reflection of the electrical pulse. Second, the rise and fall times of the DSOA are 434 and 536 ps, respectively, corresponding to a 40% reduction compared to the SOA devices which has a rise and fall time of 900 ps. This improvement is in part due to the small differences in the geometry of the devices, the bandwidth of the current drivers, and the differences in the saturation power which affects the transient response of the SOA [15]. However, the improvement is primarily attributed to the hybrid integration approach used. The transition time improvement directly affects the average truncation time τ resulting in a 67% increase in the number of cascaded node for the same specified guard time value.

IV. Conclusion

We demonstrated a 2×2 SOA-based switching node with two optimizations for optical MINs. The switching node makes use of Schmitt trigger comparators for header signal regeneration, and of a hybrid integration of an SOA device with its current driver (DSOA) reducing the guard times by 40%. These two optimizations enhance the cascadability of SOA-based switching node enabling more stages in large-scale optical MINs.

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