All-optical signal processing with standard edge-emitting laser diodes

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The recent introduction of new internet-based services results in increasing network traffic. However, the electro-optical and opto-electronic (O/E/O) conversions in the network nodes impose a technological bottleneck with respect to speed and power consumption. Therefore, all-optical signal processing techniques are required with all-optical flip-flops being one of the key building blocks. We demonstrate how standard edge-emitting laser diodes (such as DFB and DBR lasers) can be used as all-optical flip-flops. Moreover, their application in all-optical packet switching and 2R-regeneration is illustrated with experimental results.

The telecommunication industry has experienced a huge growth during the last decade and the need for bandwidth is expected to increase further as new internet-based services are being implemented. Optical fibers offer by far the best solution to transfer huge amounts of data traffic over large distances (up to 8 Tb/s over 510 km fiber [1]) and have been installed world wide. However, the electronic processing in the network nodes imposes a technological bottleneck at these high speeds. Besides the limited speed of electronic components, also the power consumption becomes an important issue: recent studies show that the total power consumption of the internet is comparable to that of the air traffic industry.

Photonics offers a solution for this problem by implementing all the necessary signal processing in the optical layer and thereby making the extremely power-consuming opto-electronic (O/E) and electro-optical (E/O) conversions redundant. In this article, an overview will be given of recent results obtained with our research on this topic. First, novel concepts for all-optical flip-flops based on single edge-emitting laser diodes will be demonstrated and a proof-of-principle of a 40 Gb/s optical packet switching is shown. We conclude by discussing a novel technique for optical regeneration to reduce noise.

All-optical flip-flops

One of the most important elements to be implemented in optical network nodes are all-optical flip-flops because of their ability to act as optical memory elements. In general, they have a bistability in the amplitude or wavelength and one can switch between the two different states by injecting an optical pulse. Many different implementations of such devices have been proposed, but the main innovation in our research is the realization of extremely fast flip-flop operation (up to 40 - 50 ps switching speeds) in single laser diodes.

The first concept for flip-flop operation that we introduce is a single distributed feedback (DFB) laser [2, 3] (Fig. 1). DFB lasers are the standard elements in today's telecommunication industry and their name originates from the the feedback mechanism which is not by reflections at the facets of the cavity, but by diffraction on a grating which is distributed throughout the cavity. The injection of light with a frequency outside the stopband of the grating causes a non-uniform carrier distribution which distorts the Bragg reflection and therefore increases the lasing threshold. This gives rise to a hysteresis effect which can be used to switch the laser on and off by injecting light pulses in the cavity from opposite sides. A holding beam from one side is necessary to work within the bistable regime.

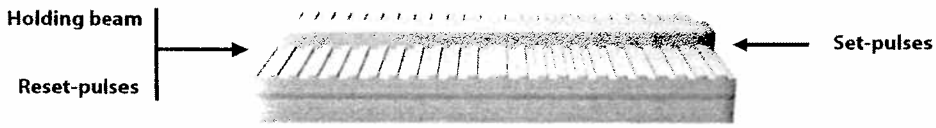

Figure 1: Schematic illustration of DFB flip-flop.

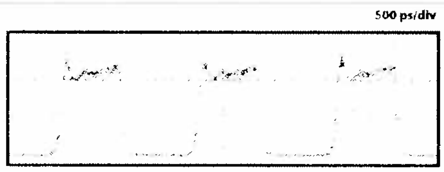

Figure 2: Experimental demonstration of flip-flop operation in a DFB flip-flop.

Another concept is based on a distributed Bragg laser where a grating is located outside the active laser section to reflect light at a specific frequency back into the cavity (wavelength-dependent mirror). By changing the current on the grating, we can tune the wavelength of the laser. However, due to mode competition within the laser cavity (Bogatov effect), a hysteresis can be observed in the wavelength tuning characteristic and therefore it is possible to injection-lock the laser on one of the two wavelengths by sending pulses at that specific frequency (Fig. 2). We also demonstrated this effect using pulses with the same frequency, but with different duration and amplitude. A long pulse is used to injection-lock the laser (as before) but a very short pulse will bring the laser in depletion so it will start lasing at the frequency with the lowest carrier density.

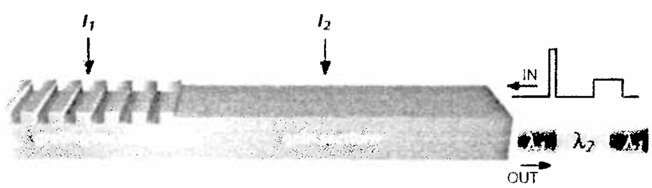

Figure 3: Schematic illustration of DBR flip-flop.

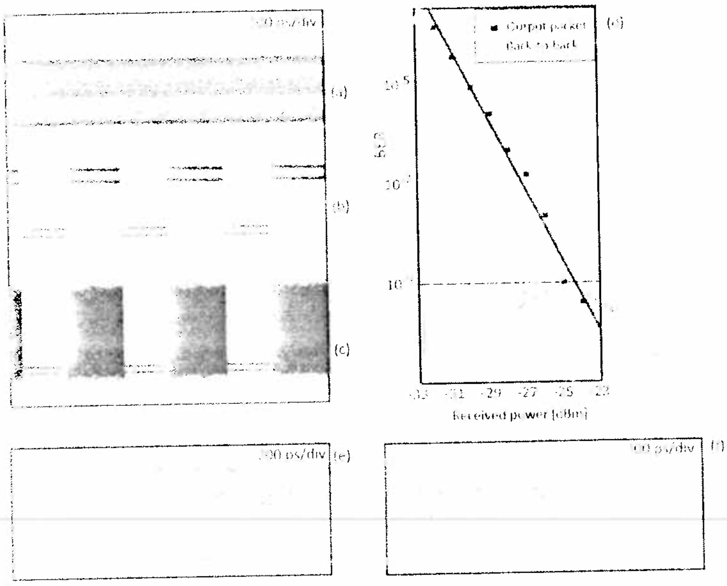

Figure 4: Results for optical packet switching with DFB AOFF (a) 40Gb/s Optical Packets and color-coded labels; (b) Output of DFB AOFF; (c) Switched optical packets; (d) BER-curves for the output and back-to-back; (e-f) transient behaviour for switch-on and switch-off.

Packet switching

In current networks, the optical packets are wavelength-division multiplexed (WDM) on different optical carriers to exploit the fiber bandwidth. These carriers can be created by an array of DFB laser diodes, each emitting light at one channel of the WDM grid. In electronic configurations, the packets are demultiplexed and converted to electrical signals by an array of photodiodes. After processing in the electrical layer, the signals are converted back to one of the optical carriers of the WDM grid.
By using an array of DFB lasers where each laser has a different lasing wavelength matched to the WDM grid, one can switch a laser in the array on and off simply by injecting an optical pulse. Such an optical pulse can originate from an all-optical header processor unit which compares the header with a predefined bit-sequence [4]. The header processor can thus switch on the DFB laser that matches the header routing information by injecting an optical pulse. Consequently, a wavelength converter can be applied to convert the packet to the wavelength of the DFB laser.
As a proof of principle, we experimentally demonstrate the use of the DFB flip-flop within an actual all-optical packet switching configuration [5]. Based on the routing information (contained in the header of a data packet), a header processor switches the all-optical flip-flop on by sending an optical pulse. The optical flip-flop stores the temporal decision of the header processor while the payload is being transferred to the right output port. An illustration of the realization of all-optical packet switching at 40 Gb/s using a DFB laser as all-optical flip-flop is shown in Fig. 4.

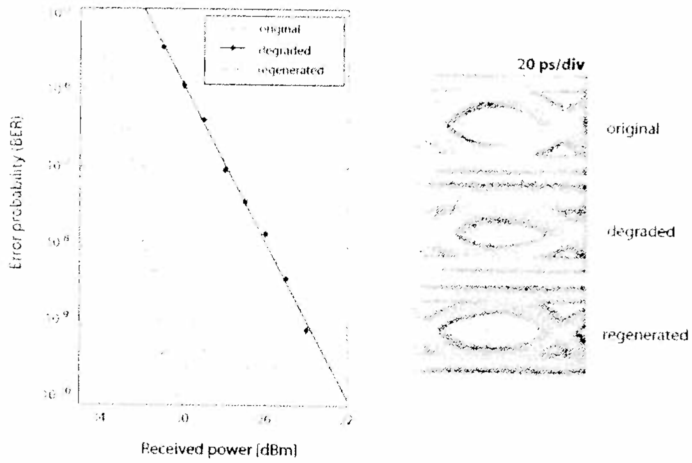

Figure 5: Experimentally achieved 2R regeneration using a DFB laser on a 10 Gb/s signal

Regeneration

One of the major concerns for the implementation of all-optical networks, is the accumulation of noise which limits the cascadability of optical network nodes and optical amplifiers. Therefore, there is a clear need for devices which can reduce the noise on signals. We propose a novel regeneration scheme where a hysteresis in the decision characteristic increases the tolerance to noise and improves the bit-error rate of the signal. Instead of the hysteresis in the lasing characteristic (used for the DFB flip-flop operation), we use now the transmission characteristic. The experimental result of the noise reduction at 10 Gb/s is illustrated in Fig. 5.

Conclusion

We demonstrated how standard edge-emitting laser diodes can be operated as all-optical flip-flops and their application in all-optical packet switching and 2R regeneration.

References

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