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Novel Scheme for Simple Label-Swapping Employing Logic XOR in an Integrated Interferometric Wavelength Converter

T. Fjelde, A. Kloch and D. Wolfson

Research Center COM, Technical University of Denmark, Bldg. 349, DK-2800 Lyngby, Denmark

Telephone: +45 4525 3808, Fax: +45 4593 6581, e-mail: tf@com.dtu.dk

B. Dagens, A. Coquelin, I. Guillemot, F. Gaborit, F. Poingt and M. Renaud

OPTO+, Groupement d'Intérêt Economique, Alcatel Corporate Research Center

Route de Nozay, 91460 Marcoussis, France

Telephone: +33 (0)1 6963 1235, Fax: +33 (0)1 6963 1813

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Abstract: We present a novel scheme for all-optical label swapping that relies on logic exclusive-OR (XOR) in an integrated SOA-based Michelson interferometer. The scheme allows simple, efficient and mechanically stable operation, while relaxing the requirements on packet format and simplifying switch management. Furthermore, the label-swapping scheme does not require a guard band between the header and payload to perform alterations in the header. The method, which incorporates simultaneous wavelength conversion, is demonstrated at 10 Gbit/s with negligible penalty and a high output signal-to-ASE ratio of ~35 dB.

Introduction: With the exponential growth in Internet traffic, scaling of IP data networks far beyond their present performances is required. In order to meet this challenge, Multi-Protocol Label Switching (MPLS) [1] is rapidly emerging as the technology that allows for enhanced speed and scalability as well as service provisioning capabilities in the Internet. All-optical packet switching exploiting WDM fits well into the MPLS concept, while offering flexibility, enabling scaling to very high bit rates and eliminating potential electronic bottlenecks.

In order to enable optical MPLS an efficient scheme for all-optical label swapping is required in packet switches (i.e., label-switching routers (LSR)). This is because the label on an incoming packet is replaced with a new value in the LSR as it is forwarded it to the appropriate outlet; thus, the forwarding mechanism is based on label swapping. Different methods for all-optical label swapping have been proposed within the last few years, including the employment of header erasure/rewriting to perform simultaneous label swapping and wavelength conversion as demonstrated in both [2] and [3]. Incorporating wavelength conversion is an advantage as it assures that header and payload maintain the exact same wavelength, which is important for dense WDM. Moreover, wavelength conversion can be used for packet contention resolution [4]. In [2] header erasure/rewriting is performed using a two-stage method that employs SOA-based cross-gain modulation followed by cross-phase modulation, while in [3] header replacement is done at 2.5 Gbit/s in a single step using a loop mirror.

This paper presents an alternative method for all-optical label swapping that does not require complete header erasure/rewriting; only a few header bits in the label are changed using a short “swapping sequence”, while the remaining header and payload are left unaltered. Thus, the complexity of switch management is reduced significantly, which, of course, is an important factor for the implementation of all-optical networks. Furthermore, since no header replacement is done a guard band between the header and payload is not necessary for this scheme. This means that a more

efficient use of bandwidth is possible. The scheme relies on optical XOR in a monolithically integrated interferometric wavelength converter (IWC) to perform simultaneous label swapping and wavelength conversion in one stage. In this paper, the label swapping scheme is demonstrated at 10 Gbit/s with a negligible penalty of 0.4 dB using a Michelson interferometer. Due to its simplicity, stability and power-efficiency the method is easy to implement in practice, clearly demonstrating the feasibility of all-optical label swapping in future networks.

Principle of logic XOR in an interferometric wavelength converter: As mentioned previously, the label swapping scheme proposed in this Letter relies on all-optical logic XOR in an IWC. In Fig. 1 the principle of logic XOR in a Michelson interferometer (MI) is shown schematically. As indicated in Fig. 1a, two input data signals on which the logic operation is to be performed are coupled into the interferometer arms at port #1 and 2, while CW-light is coupled into the common arm at port #3. In the MI the data signals are launched into the two SOAs where they modulate the carrier density and thereby also the refractive index. This causes a phase modulation (ϕ) of the CW-light propagating in the SOAs according to the bit pattern of the input data signals. At the output of the interferometer, the CW-light from the two SOAs interferes either constructively or destructively depending on cosine to the phase difference between the light from the two SOAs ($\cos(\phi_1 - \phi_2)$) and is thus controlled by the input data signals. This leads to a wavelength converted output signal at port #3 that corresponds to the logical XOR of the two input data signals, as indicated by the truth table shown in Fig. 1c. Note that the CW-light is reflected from the end facets at ports #1 and 2, why it propagates twice through the SOAs before exiting the MI at port #3.

The capability of the interferometric wavelength converter as an XOR gate has previously been demonstrated at up to 20 Gbit/s in [5], where a Mach-Zehnder interferometer was employed. Furthermore, standard 40 Gbit/s wavelength conversion has been performed in a Michelson interferometer [6], indicating the high-speed potential of the IWC.

Practical implementation of label-swapping scheme: In Fig. 2 is shown a schematic of the label swapping scheme with the interferometric XOR gate as the central element to change selected bits from marks to spaces and vice versa. Label swapping is achieved in the following way: At the packet switch input, a fraction of the signal power in incoming packets is tapped off to the switch management to perform header clock recovery, packet delineation, label reading, etc., -all necessary for any header modifications. Using this information, the changes needed in the existing label are found and, at the appropriate time, modulated onto CW-light at a fixed internal wavelength λ_{int} . The optical swapping sequence is coupled into one of the interferometer arms (here, port #2), while the input packet at λ_{in} is coupled into the other. Furthermore, CW-light at the desired output wavelength, λ_{out} , is coupled into port #3. Through cross-phase modulation as described above, the output packet at λ_{out} will correspond to the logic XOR of the input packet and the swapping sequence. So, a space in the swapping sequence will leave the input data bit unchanged at the output, while a mark will alter the bit in the output packet with respect to the input packet. Note that the scheme places no restrictions on the bit-rate of the payload data, which can be variable.

Experimental set-up: Figure 3 shows the experimental set-up used to investigate the label swapping scheme at 10 Gbit/s by bit-error rate (BER) measurements on the output packet sequence. In order to avoid the use of two pattern generators for the input packet sequence and the label swapping sequence, the following scheme has been used: 10 GHz clock pulses having a pulse width of ~30 ps are generated through modulation of CW-light at 1538 nm using an EA-modulator. A 10 Gbit/s data sequence consisting of the input packet sequence followed by a label swapping sequence (Δ) is encoded onto the RZ pulses using a LiNbO₃ modulator. As shown in Fig. 3, the signal is passively split into two arms. By subsequently delaying one part appropriately with respect to the other, the swapping sequence will be injected into one arm of the all-active Michelson interferometer in synchronisation with the packet header injected into the other arm. Both signals have input power

levels below -3 dBm, demonstrating the power efficiency of the scheme. In addition, $+3$ dBm of CW-light at 1543 nm is coupled into the MI at port #3. Exiting port #3 is the wavelength converted output packet sequence with a power of -1.5 dBm. This demonstrates conversion gain as the output signal level exceeds the input signal level. Finally, a filter selects the output packet sequence before detection and error counting.

Results and discussion: Figure 4 shows the measured pulse traces of input and output packet sequences. To enable illustration of all bits in the packet sequence clearly at the same time the packet has a limited length of 123 bits with a 23-bit header, a 7-bit guard band and a 93-bit payload. As indicated, the input and output packet sequences are identical except for the bits in the header that have been altered by the label swapping scheme. Note that the variation in the height of the marks is primarily due to the limited resolution of the oscilloscope used and not actual power fluctuations. This is verified in Fig. 5, which shows an enlarged version of the input header and partial payload along with the corresponding label swapping sequence and output header. Four marks in the label swapping sequence change the corresponding bits in the input packet sequence. As the output packet trace indicates, this has been performed successfully; an input mark is changed to an output space and vice versa. Note that, as mentioned previously, a guard band between the header and payload is not necessary for this scheme. Here, it is inserted only to visually separate header and payload.

To fully verify the performance of the label swapping scheme, bit error rate measurements have been performed on the input and output packet sequences shown in Fig. 4. In both cases, error counting was done on both the header and payload simultaneously. The results are shown in Fig. 6, indicating that the label swapping is performed with a negligible pre-amplified receiver penalty of 0.4 dB. The clear and open output packet eye diagram, shown as an insert, demonstrates that the header bits have been altered without signal quality degradation. Furthermore, the high output

signal extinction ratio of ~13 dB that is obtained indicates the good performance of the scheme. It should be mentioned that the XOR gate has also been tested with a comparable performance on longer bit sequences. The optical spectrum at the output of the MI is shown in Fig. 7, which demonstrates that the output packet sequence exhibits a high signal-to-ASE ratio of ~35 dB (in a 0.1 nm resolution bandwidth). This high signal-to-ASE ratio is an essential factor for cascadability. Finally, it should be mentioned that the scheme is not restricted to the RZ modulation format; logic XOR has previously been demonstrated in [7] at 5 Gbit/s in an integrated Mach-Zehnder interferometer using the NRZ modulation format.

Conclusion: In this Letter, a novel scheme for all-optical label swapping has been presented. It relies on logic XOR in an integrated SOA-based interferometric wavelength converter and provides significant advantages including simplicity, low power consumption, relaxed requirements to packet format and reduced switch management complexity. Furthermore, the scheme does not require a guard band between header and payload. A negligible pre-amplified penalty of 0.4 dB and a signal extinction ratio of 13 dB demonstrate the excellent performance of the scheme at 10 Gbit/s. This shows the feasibility of optical label swapping even at high bit rates.

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Figure captions

Figure 1:

- (a) Schematic of Mach-Zehnder interferometer as an XOR gate
- (b) Illustration detailing the principle of XOR operation
- (c) XOR truth table.

Figure 2: Practical implementation of label swapping scheme (MOD: modulator).

Figure 3: Experimental set-up for verification of label swapping scheme at 10 Gbit/s.

Figure 4: Measured input and output packet sequences.

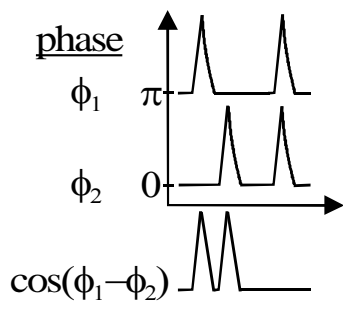
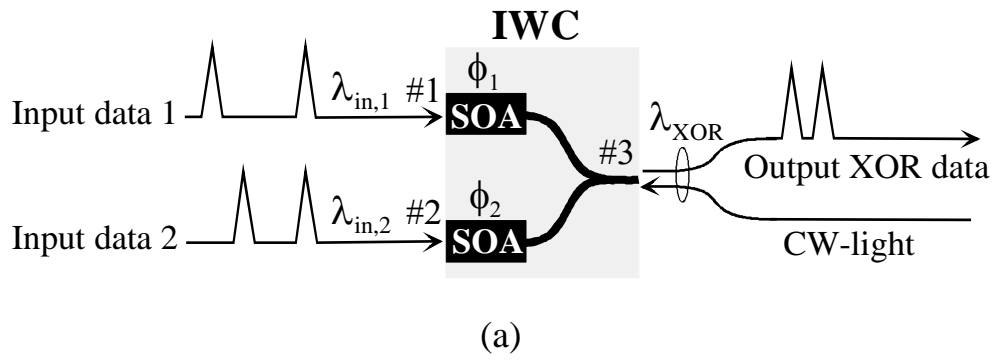
Figure 5: Scheme verification- enlargement of header (H) and partial payload (P).

Figure 6: BER vs. received power for input and output packet sequences.

- Back-to-back at 1538 nm
- Output XOR at 1543 nm

Eye-diagram for the output packet is shown as an insert.

Figure 7: Optical spectrum at output of Michelson interferometer (resolution bandwidth 0.1 nm)



(b)

Port number		
#1 (IN1)	#2 (IN2)	#3 (XOR)
0	0	0
0	1	1
1	0	1
1	1	0

(c)

Figure 1

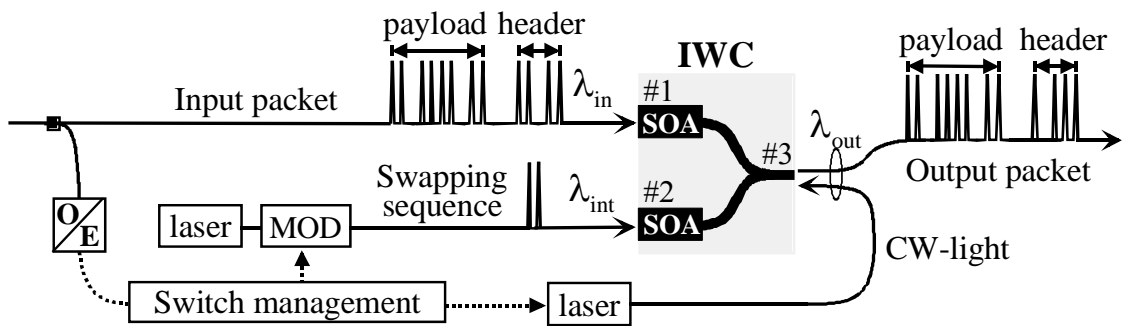


Figure 2

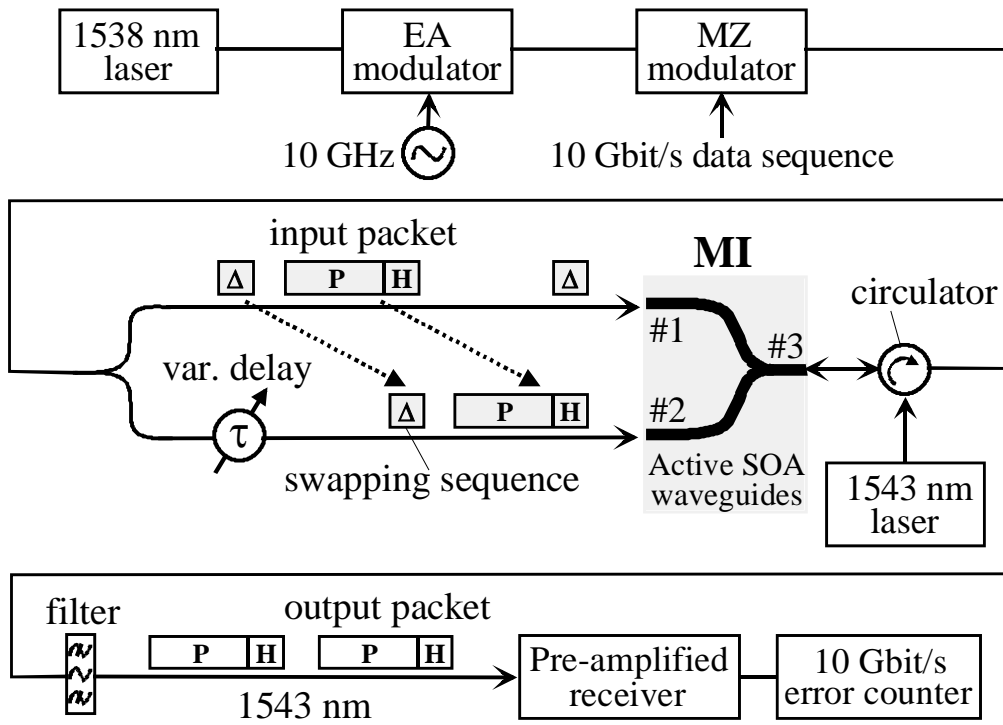


Figure 3

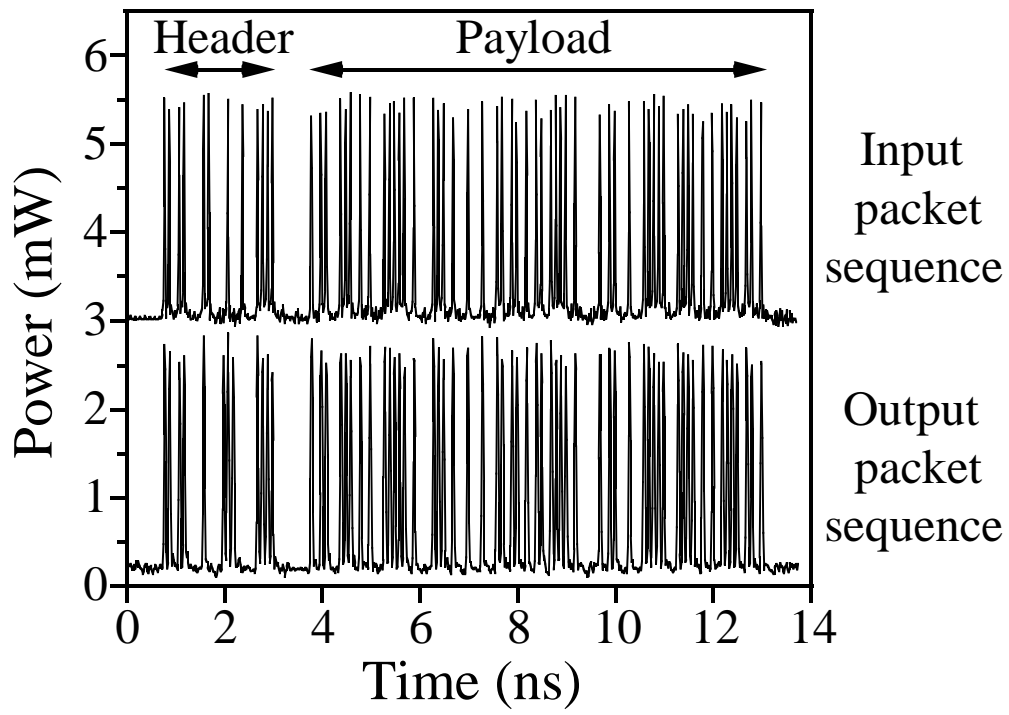


Figure 4

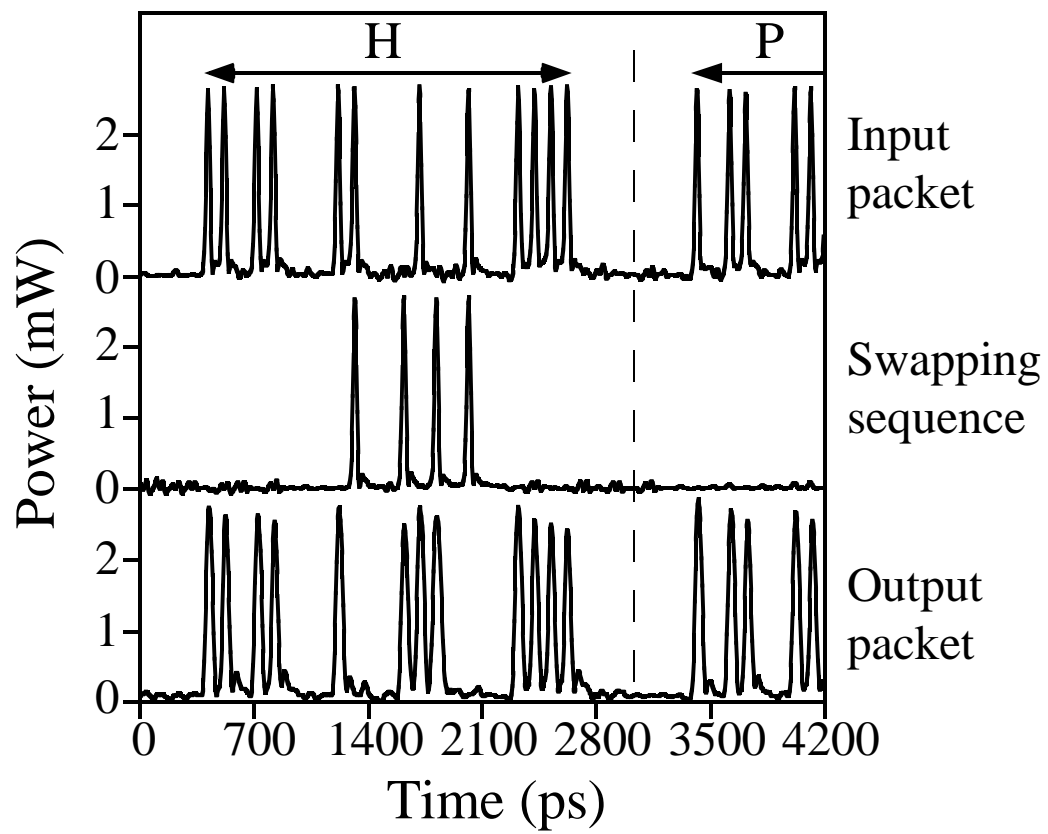


Figure 5

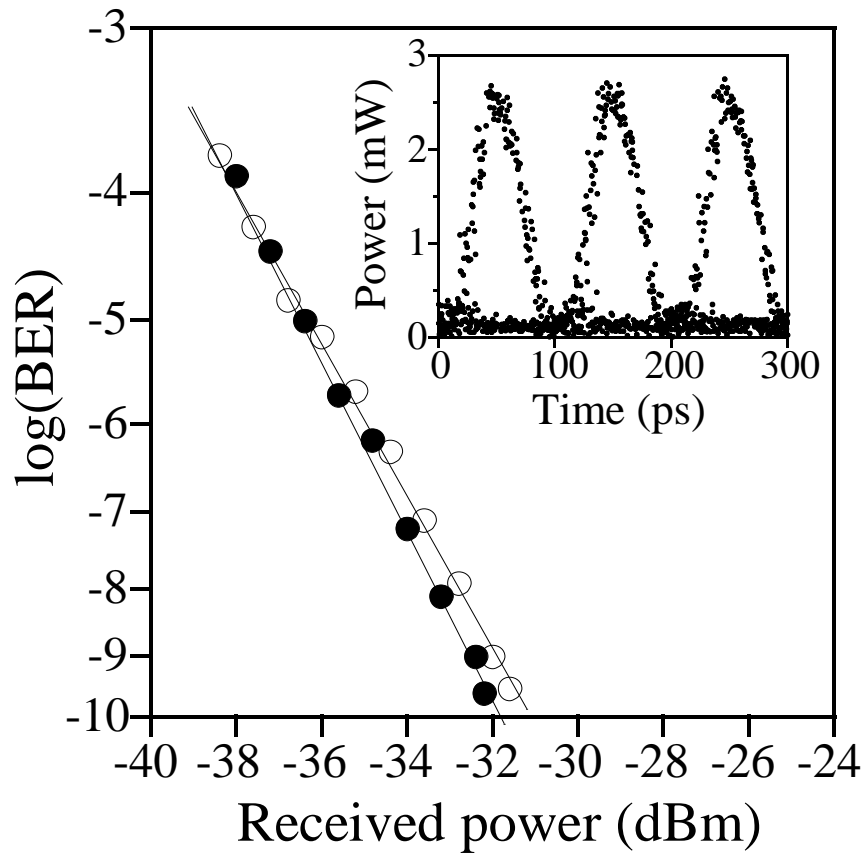


Figure 6

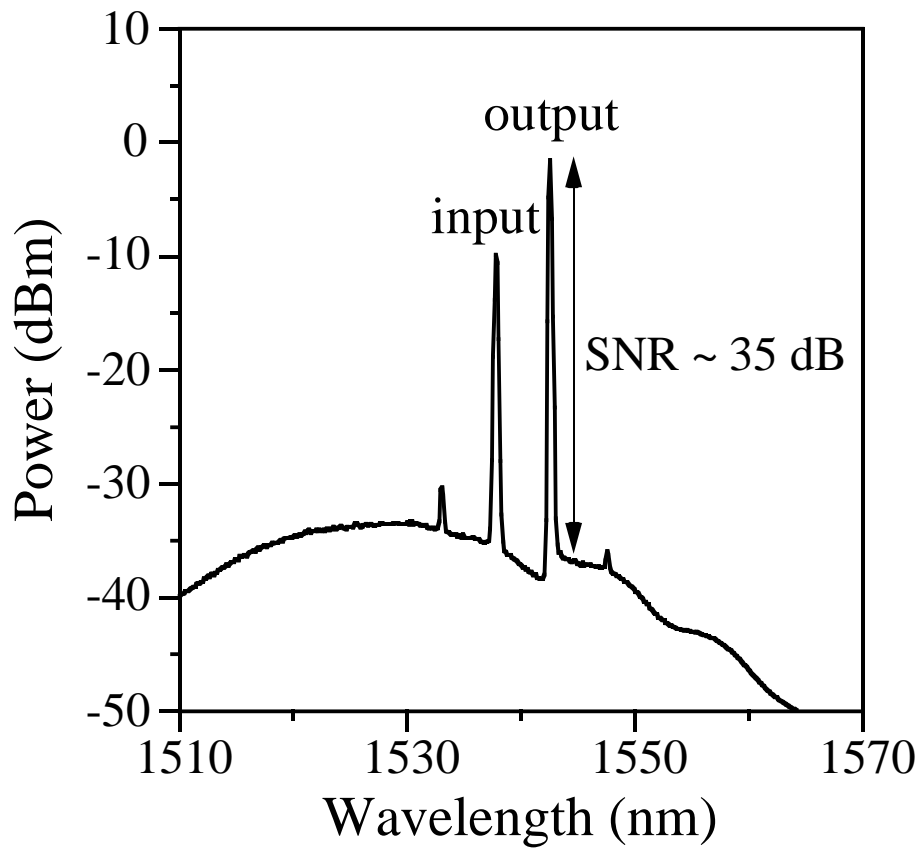


Figure 7