

Novel 3R Regeneration by Light-Holding SOA's at Transparency in a Mach-Zehnder Configuration

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A novel optical decision gate based on a Mach-Zehnder interferometer with light holding semiconductor optical amplifiers at transparency in each arm is proposed. Simulation results predict excellent reshaping function and adjustable decision characteristics by varying the holding light power and wavelength in both amplifiers.

Keywords: optical decision gate, reshaping, Mach-Zehnder interferometer, semiconductor optical amplifiers, decision threshold

Introduction

All-optical regeneration will be essential in future high-speed optical systems to suppress the accumulation of noise and jitter, which severely limit the network node cascading. Several techniques for all-optical regeneration have been investigated, and some of the most promising results have been achieved with interferometric wavelength converters (IWCs). In these devices, 2R regeneration is accomplished due to the nonlinear transfer function of the converter [1]. Nevertheless, the amplitude imbalance decreases the extinction ratio of the interferometer.

Improved regeneration was proposed utilizing an interferometric structure incorporating gain-clamped SOAs (GCSOAs) as phase shifters [2,3]. However, relaxation oscillations and dark holes are present due to interaction between the internal laser light and the amplified signal via the carrier density.

A SOA configuration proposed by Dupertuis [4], called OSAT (optical speedup at transparency), uses an assist light beam injected at the transparency point of the SOA, which gives rise to very high speed operation at a current identical to that of a conventional SOA, without reducing the available gain or gain bandwidth, and without relaxation oscillations or dark holes. Here, a numerical simulation for the proposed all-optical decision gate (AODG) by incorporating two light holding SOA's at transparency into both arms of a Mach-Zehnder interferometer is conducted. We predict the excellent 2R regeneration characteristic from our novel structure.

SOA model for numerical simulation

In order that the carrier dynamics can be studied along the length of the amplifier, the SOA is segmented into a number of smaller sections. In our model, the SOA is divided into 20 longitudinal sections of equal length, and a simplified model with uniform carrier and averaged photon densities is used for each section. The ASE spectrum is divided into 32, 16-nm-wide, spectral slices. The accurate description of the spontaneous emission is essential to reveal gain saturation effects caused by ASE, that are relevant for small-signal intensity and/or high current injection.

In this work we consider the InGaAsP direct bandgap bulk-material active region, taking into account light- and heavy-hole band transitions, energy gap dependence on carrier density, and the quasi-Fermi levels are calculated according to the Nilsson approximation. The material gain g_{m_i} is given by

$$g_{m_i}(\hbar\omega) = \frac{\sqrt{2}(m_r^*)^{3/2} e^2 |M_T|^2}{3\pi m_r \epsilon_0 m_0^2 \hbar^2 c \cdot (\hbar\omega)} \cdot (\hbar\omega - E_g)^{1/2} \cdot [f_n(E_2) - f_p(E_1)]. \quad (1)$$

Electron-rate equations are then applied to each section of the cavity in stationary conditions (i.e., $dN/dt = 0$).

$$\frac{dn_i}{dt} = \frac{I}{qwdL} - \frac{n_i}{\tau_{si}} - \sum_{k=1}^N v_g g_{m_{ik}} S_{av_{i,k}} - v_g g_{m_i} \cdot (S_{av_{i,sp}} + S_{av_{i-1,ASE}}) \quad (2)$$

Here, the subscript i corresponds to the different amplifier sections and k refers to the different optical input beams. n_i is the carrier density in section i ; t is the time; I is the drive current; q is the electronic charge; and d , L and w are thickness, length, and width of the SOA, respectively. $\tau_{si} = (A + Bn_i + Cn_i^2)^{-1}$ is the carrier recombination lifetime in section i , $g_{m_{ik}}$ is the material gain in section i for input beam k . v_g is the group velocity, and $S_{av_{i,k}}$ presents the average photon density in segment i of the SOA cavity and for beam k . We neglect the facet reflectivity of the SOA in this paper. The ASE stimulated recombination depends on both the spatially averaged spectral density of spontaneous photons generated within the i th section and on the spatially averaged spectral density of ASE photons, generated in all sections, that enter the i th section from both sides. All parameters of the SOA are shown in Table I.

Table 1. PARAMETERS OF THE SOA

Parameters	Value
Recombination coefficient, A	$2.8 \times 10^8 \text{ s}^{-1}$
Recombination coefficient, B	$4.3 \times 10^{-17} \text{ m}^3 \text{ s}^{-1}$
Recombination coefficient, C	$8.0 \times 10^{-41} \text{ m}^6 \text{ s}^{-1}$
SOA length, L	1 mm
Active layer width, w	2.5 μm
Active layer thickness, d	0.25 μm
Carrier density at transparency, n_0	$1.1 \times 10^{24} \text{ m}^{-3}$
Confinement factor, Γ	0.35
Internal loss, α	$(62 + \Gamma \cdot 75 \times 10^{-24} \cdot n) \text{ cm}^{-1}$
Refractive index, n_{eff}	3.5
Change in refractive index with carrier density, dn/dN	$-1.2 \times 10^{-26} \text{ m}^3$
Carrier density at original threshold, n_{th}	$3 \times 10^{24} \text{ m}^{-3}$

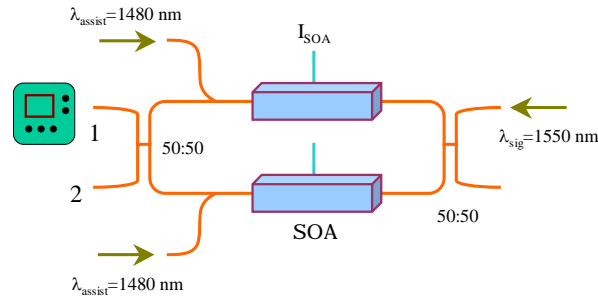


Fig. 1. Symmetrical MZI-based implementation of an optical decision gate.

The transparent condition of a SOA corresponds to the condition that the material gain of the SOA is zero for the incident wavelength. The transparent current for an assisted beam can be determined from comparing the gain-vs-current curves at a given wavelength between the presence and absence of the assisted beam. The transparency locates at the intersection of the two curves

since the gain is not changed for the presence of the assisted beam. We depict the gain curves at 1550 nm for the cases with and without a 1460-nm assisted beam. The two curves intersect at 135 mA of bias current, which corresponds to the transparent current for the 1460-nm light. The transparent current is larger for a shorter wavelength. Results also show that the assisted beam does not affect the unsaturated gain at the transparent condition and raises the saturation power by ~5dB.

Simulation results on the MZI

The regenerator has a Mach-Zehnder interferometric structure with light holding SOAs (LHSOAs) in both arms (Fig. 1). The operation of this regenerator is based on the specific property of a LHSOA that its amplification in the linear regime is independent of the holding light power. Calculated characteristics of 2 LHSOA's with different holding light powers at transparency are shown in Fig. 2. The LHSOA's are assumed to be completely identical and to have a different holding light power. They, therefore, give an identical and constant amplification and phase shift below the saturation power, but they exhibit a different saturation power. In the linear regime, both arms of the MZI give the same signal gain and a constant phase delay. If we compensate the phase delay, a completely destructive interference below the input saturation powers of both LHSOA's is obtained at the output of the MZI. As can also be seen in Fig. 3, above the saturation power of both LHSOA's, the phase difference between both arms is also constant, and the output powers from both LHSOA's are saturated, such that a constant output power is also obtained at the output of the MZI and hence a digital-like decision characteristic is achieved with the MZI regenerator. Furthermore, different decision characteristics such as output 1 levels can be obtained by varying the holding light power in both amplifiers (Fig. 3). A utilization of this function is the AGC (Automatic Gain Control) amplifier in the receiver of a fiber optic data link, whose purpose is to adjust automatically receiver gain according to received signal amplitude.

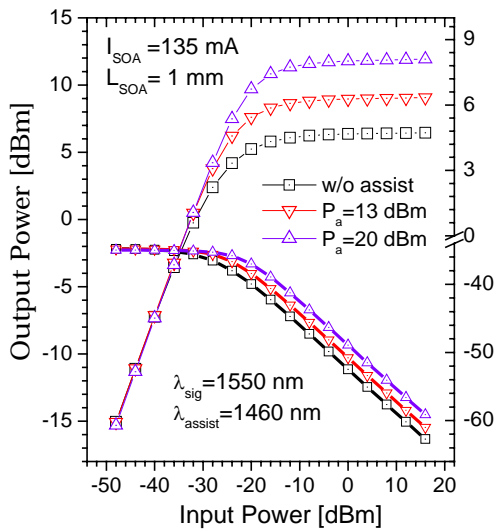


Fig. 2. Amplitude and phase characteristics of LHSOA's with different holding light powers.

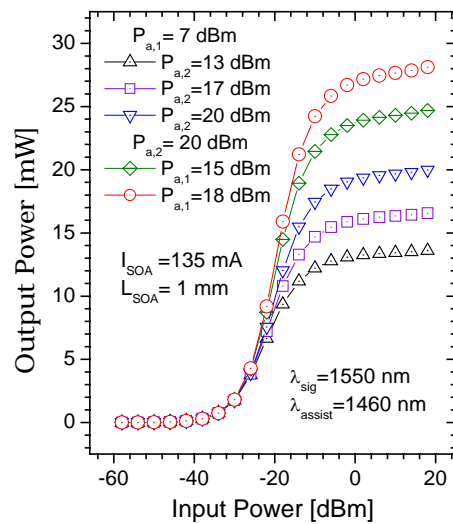


Fig. 3. Output power versus input power of a symmetric decision gate.

In general, the decision threshold is fixed and determined by the structure and, therefore, can't be modified to take into account the properties of the incoming signal. In our scheme, however, the decision threshold can alter by changing the spectrum characteristics of the assist light. Accordingly, higher injection current is set to make the waveguide transparent for the assist light shift to shorter wavelength. By doing this, the material gain will increase to cause a larger differential gain for the

signal light. A smaller input saturation power that determines the decision threshold is thus attained due to the promoted differential gain as shown in Fig. 4.

To meet the practical requirement for future all-optical 3R regeneration, a novel scheme based on the LHSOA is proposed. A clock light with constant power $P_{a,2}$ is introduced into the SOA on either arm of MZI. The data signal light is lunched into the input port of AODG. The ON/OFF of the control clock pulses stimulates the timing extraction of distorted data signal and the power determines the output 1 level of the reshaped data signal. Schematic diagram of this device and the relationship of output 1 level versus peak power of clock pulses are displayed in Fig. 5. The AODG works and 2R regeneration is evaluated for the incoming data signal only when $P_{a,2}$ is ON. Reamplification, reshaping and retiming of the distorted data signal can thus be performed via the control of clock pulses. Clearly, this novel device can represent all-optical 3R regeneration.

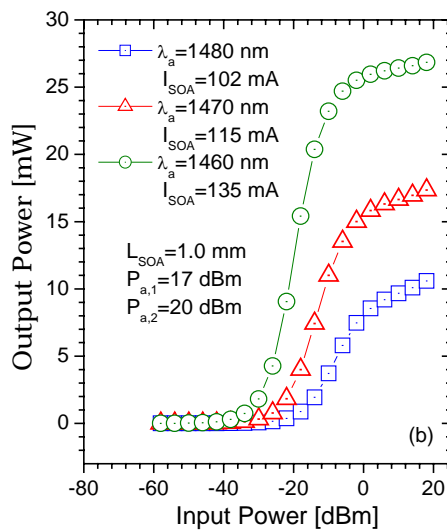


Fig. 4. Output power versus input power of a symmetric decision gate with different wavelength of assist light.

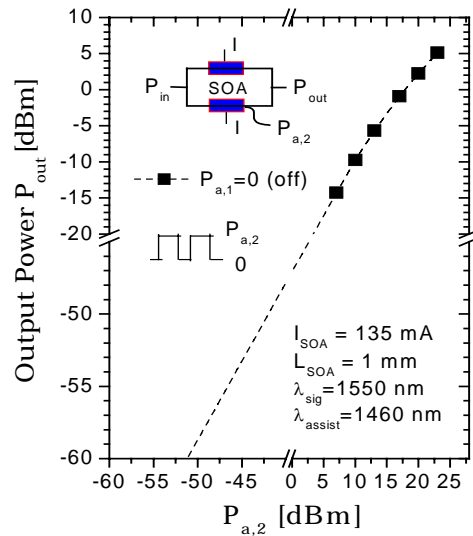


Fig. 5. Output 1 level of all-optical decision gate versus control clock light power.

Conclusions

We have reported new structures utilizing light holding SOAs at transparency to allow for all-optical 2R signal regeneration. Numerical simulations of the structures have been performed and have shown nearly ideal optical decision characteristics results. Improved gain recovery and no relaxation oscillations or dark holes could remove the speed limitation occurred in the GCSOA. Setting the waveguide transparent for the assist light in the shorter wavelength range will lead to a smaller decision threshold, which is mainly caused as a result of enhanced differential gain. Novel application is also proposed for future all-optical 3R regeneration system.

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