Two-section semiconductor optical amplifier used as an efficient channel dropping node

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damping factor is significantly enhanced in this region, as compared with the value calculated from (9). Similar experimental results in the case of current modulated laser diodes have been reported by Olshansky *et al.* [6]. However, its physical origin is not clear at the time of writing.

In conclusion, although a limited system bandwidth (~ 3 GHz) restricted our experiment within a limited injection current ($I/I_{th} = 1.3$), this letter presents a viable means for measuring the gain compression factors of DFB lasers in the presence of TM light injection.

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Two-Section Semiconductor Optical Amplifier Used as an Efficient Channel Dropping Node

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***Abstract*—We describe high responsivity in a two-section semiconductor optical amplifier/detector serving as a channel dropping node. A simple receiver constructed using a 50Ω amplifier with a sensitivity of −30.2 dBm at 140 Mb/s is demonstrated.**

Introduction

The use of semiconductor optical amplifiers (SOA) for simultaneous amplification and detection has recently been demonstrated [1]–[3]. Two-section SOA's (TSSOA) [4], [5] offer improved flexibility and functionality and have also been proposed as high responsivity detectors [4]. We propose here the use of a TSSOA as a channel dropping amplifier/detector in the context of bus-configured networks. The role of a TSSOA in such a network is shown schematically in Fig. 1 where the back section is used as a highly efficient detector because of the low carrier density and the front section is used as an optical amplifier in order to compensate for losses. The TSSOA provides just sufficient gain to keep the power along the bus constant while it also serves as a photodetector at each node. The responsivity of the amplifier/detector is very high due to the optical gain so that reasonably high sensitivity receivers can be obtained at each node using simple 50 Ω electronic amplifiers. We describe the characteristics of TSSOA and present measured results for the responsivity dependence on modulation frequency and input power as well as bit-error-rate measurements at a data rate of 140 Mb/s.

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Device Description

The two-section amplifier is a 600 μm long BH-type amplifier with a 0.2 μm thick active layer grown by GSMBE [7]. The amplifier and detector sections are 400 and 200 μm long, respectively. AR coatings on both facets give reflectivities of approximately $5 \cdot 10^{-4}$. In the experiments, the amplifier section is biased at 90 mA, which results in a gain of approximately 20 dB in that section for TE polarized light while the gain for the TM polarized light is 5 dB smaller. The detector section is shorted to ground through a 50 Ω resistor and a RF-choke. However, free carriers will exist in the detector section because of leakage current and optical pumping due to the spontaneous emission from the gain section. Therefore, the responsivity will be limited by the carrier lifetime and not by the equivalent *RC* network. The absorption in the detector section is estimated to 10 dB resulting in an overall insertion loss around 0 dB for the particular device when the coupling losses of 5 dB per facet are accounted for. Thus the incoming datastream is passing

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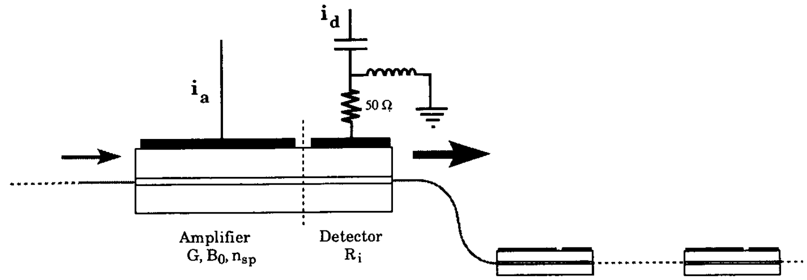

Fig. 1. Two-section semiconductor optical amplifier in a bus configuration. G is the chip gain, B_o optical bandwidth, n_{sp} the spontaneous emission parameter and R_i the internal responsivity of the detector section.

the device without significant losses while the ac component of the detected signal is coupled to the electronic amplifier through a blocking capacitor.

Responsivity Measurements

The responsivity of the TSSOA is defined as the ac-component of the generated photocurrent divided by the incident modulated optical power. It should be noticed that the optical power is measured at the input fiber. Fig. 2 shows measured responsivities as a function of modulation frequency and input power. Theoretically predicted curves are also shown and are in good agreement with the measured data. The theoretical curves are calculated using [1]

$$R = \eta G \frac{R_{\max}}{\sqrt{1 + (\omega\tau)^2}} \quad (1)$$

where η is the coupling efficiency, G the gain in the amplifier section, and ω the angular modulation frequency of the injected signal. $R_{\max}$ is the maximum responsivity for the detector section, and is proportional to the carrier lifetime τ and the wavelength λ and is given by

$$R_{\max} = \frac{1}{hc_o eV}\frac{dE_f}{dN}(G_{sa} - 1)\lambda\tau \approx -\frac{\lambda\tau}{hc_o eV}\frac{dE_f}{dN} \quad (2)$$

where h is Planck's constant, c_o is the velocity of light in vacuum, e is the electron charge, and V is the volume of the active region. dE_f/dN is the differential quasi-Fermi level difference with respect to the carrier density N, which can be attained from [9]. At low carrier densities dE_f/dN is inversely proportional to N which means that $|R_{\max}|$ increases when the carrier density decreases. Since the single pass gain G_{sa} in the detector section is small ($G_{sa} \ll 1$) it can be omitted as shown in (2).

As seen from Fig. 2, a responsivity up to 34 A/W is measured at low frequencies. This responsivity is approximately 30 times higher than that obtained with single electrode SOA's [1] and is evidently due to the gain of the input section. The bandwidth is about 80 MHz and is determined by the carrier lifetime in the detector section. For higher detection bandwidths the response can be equalized. Based on the data of Fig. 2, a 400 MHz bandwidth can be obtained using a simple passive equalizer [6]. The expected responsivity would then be 6 A/W. The bandwidth can also be extended by reverse biasing the detector section which then will be RC limited and act as an conventional detector. The reverse bias will enhance the absorption and consequently a short detector section is necessary in order to obtain zero insertion loss for the component.

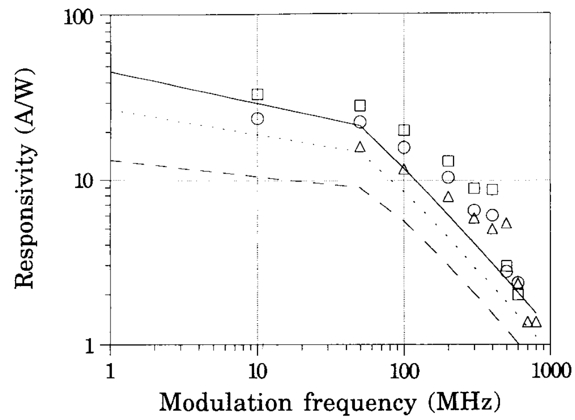

Fig. 2. Measured and calculated responsivity versus modulation frequency of the input signal. The squares, circles, and triangles are measured at input powers of −27, −22, and −17 dBm, respectively.

The responsivity depends on the signal wavelength, the length of the detector section, and on the polarization. The wavelength dependence is determined by the gain and absorption spectra of the gain and the detector section but is mainly determined by the steep absorption curve in the latter. From measurements we have found a 3 dB decrease in responsivity for an increase in signal wavelength from 1511 to 1551 nm. Reducing the length of the detector section will give a higher carrier density (lower carrier lifetime) due to leakage current from the gain section and the optical pumping and thereby increase the bandwidth but at the same time reduce the responsivity as seen from (1). Reducing the length of the detector section will also increase the output power due to a lower absorption so a tradeoff between responsivity, bandwidth, and absorption exist when considering the length of the detector section.

The responsivity for TM light is expected to be 4–6 dB lower than for the TE polarized light used in these experiments [7]. However, the polarization sensitivity can be reduced by use of squared shape active waveguides [7]. The decrease in responsivity for the increased input powers observed in Fig. 2 is explained by the increased carrier density due to stimulated absorption in the detector section. This leads to lower responsivity and larger bandwidth as seen from (1) and (2).

Bit-Error-Rate Experiment

The TSSOA is tested at 140 Mb/s using a simple receiver constructed with a 50 Ω amplifier whose gain is 40 dB in a 98 MHz bandwidth. From the measured bit-error-rate curve in Fig. 3, the sensitivity at a BER of 10^{-9} is −30.2 dBm (measured in the input fiber). The solid curve in Fig. 3 gives our theoretical prediction showing that the penalty due to experimental imperfections is only 4 dB. This penalty is partly due to intersymbol interference caused by the detector-section bandwidth, which for 140 Mb/s, should ideally be 100 MHz. The amplifier section has a saturation input power of −10 dBm which together with the −30.2 dBm sensitivity results in a 20 dB dynamic range. In the context of the bus configuration, the sensitivity as such is not a very important parameter since the network power can be quite high and hence the demonstrated sensitivity is sufficient. Ultimate performance depends on the amplified spontaneous emission from the amplifier section and could be improved by 5 dB if optical filtering with a bandwidth of 3 nm is applied between the sections.

Discussion

The signal to noise ratio of the TSSOA receiver can be expressed for the high gain regime by a simple expression that neglects the signal-spontaneous beat noise

$$\left(\frac{S}{N}\right) \approx \frac{P_{\text{in}}^2}{\left(2n_{\text{sp}}^2 B_o E^2 + N_{\text{th}}/R^2\right) B_{\text{el}}} \qquad (3)$$

with $R = \eta \cdot R_i \cdot G$ being the external responsivity where η is the coupling efficiency, R_i is the internal responsivity of the detector-section, and G is the net gain. P_{in} is the input power, n_{sp} the spontaneous emission parameter, E the photon energy, B_o and B_{el} are the optical and electrical bandwidths, respectively, and N_{th} is the thermal noise. We note the significance of the high responsivity that eliminates the contribution of the thermal noise and hence allows the use of simple 50 Ω amplifiers.

Fig. 4 shows calculated BER curves with the responsivity R as a parameter. Using the responsivity values mentioned above, an improvement of approximately 10 dB in the sensitivity is predicted for the TSSOA compared to a single section device.

Summary

We have presented the characteristics of a TSSOA operating as an amplifier/detector channel dropping node. The device exhibits very high responsivity and therefore it is possible to use it in conjunction with simple 50 Ω amplifier receivers. This responsivity can be further improved by reducing the input coupling loss to the amplifier. In principle, such a TSSOA could be used as a node in either a bus or a ring configuration network and could also be used as a modulator [8] to impress data onto the network.

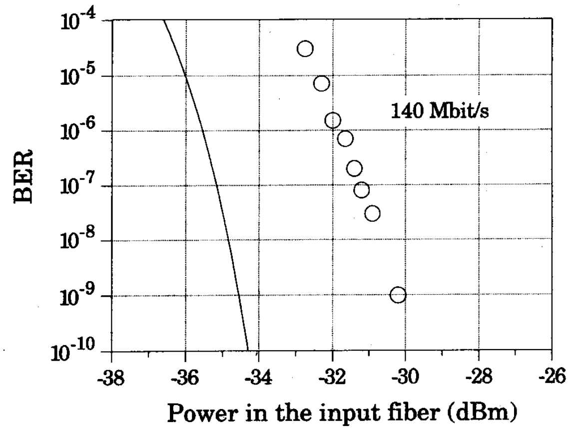

Fig. 3. Measured bit error rate as a function of power in the input fiber. The solid curve is theoretically predicted using the following values: n_{sp} = 2.5, B_o = 60 nm, B_{el} = 100 MHz, $G \cdot R_i$ = 20 A/W.

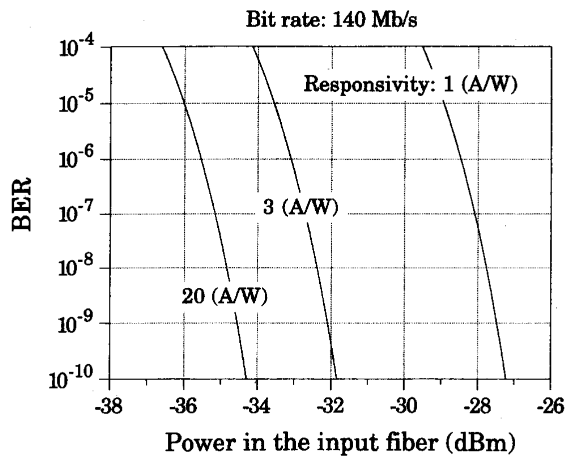

Fig. 4. Calculated bit error rate as a function of power in the input fiber with responsivity as a parameter. The parameter values used in the calculations are given in Fig. 3.

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Gain and Noise Penalty for Detuned 980-nm Pumping of Erbium-Doped Fiber Power Amplifiers

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Abstract—**The impact of altering the fiber length and pump wavelength on the gain and noise performance of erbium-doped fiber power amplifiers pumped in the 980-nm band is examined. A gain penalty of <0.5 dB was experimentally observed over a 18-nm pump wavelength range. Theoretical analysis indicates that increasing the NA from 0.15 to 0.25 significantly improves the tolerance for a given gain penalty but has little effect upon noise figure. For a given fiber length, the noise figure increases by 0.1 dB for each 3 nm the pump wavelength deviates from 979 nm.**

Introduction

THE very efficient [1]–[3] but relatively narrow 980-nm absorption band of erbium (FWHM $\approx$ 16 nm for Al/Er and $\approx$ 11 nm for Ge/Er silica) poses a serious problem for the manufacturers of semiconductor pump sources for erbium-doped fiber amplifiers (EDFA's). The low yield for devices within a few nanometers of the peak significantly increases their cost, and relaxing the wavelength tolerances for these lasers would significantly reduce the cost of 980-nm pumped EDFA's. We have performed a detailed experimental and theoretical investigation of power amplifiers pumped between 960 and 1000 nm. This has enabled us to determine the quantitative relationship between pump detuning and the penalty for both gain and noise figure, as well as the dependence of these penalties on pump power, fiber length, and waveguide design. The experiments indicate that pumping away from the peak of the absorption band leads to a gain penalty that decreases with pump power and fiber length. Using an accurate numerical model we show how a broad pump window around 980 nm can be obtained for power amplifiers by appropriate choice of fiber length and design, albeit with a degradation of noise figure.

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Experimental

The experimental setup has been described in [3]. A Ti:sapphire laser provided codirectional pumping at wavelengths ranging from 960 to 1000 nm. The pump and 1551-nm signal were combined by a WDM fiber-coupler, and the pump power launched into the doped fiber was monitored for each pump wavelength in the experiment.

Fig. 1 displays the signal output power as a function of pump wavelength for a Ge/Al/P/Er-doped silica fiber with an NA of 0.18 and a cutoff wavelength of 940 nm. The signal launched into the erbium-doped fiber was -1.4 dBm. The experimental results are indicated by marks for three different fiber lengths each pumped with 40 and 80 mW. The solid curves are computer simulations of the experiment obtained using a numerical model described previously [4]. All basic parameters used by the model were determined experimentally and the calculated values are seen to be in good agreement with experiment. Also indicated in Fig. 1 is the ground-state absorption (GSA) cross section spectrum which peaks at 979 nm. As expected, signal output and quantum conversion efficiency increase with pump power, reaching 16.3 dBm and 0.83, respectively, for the 16 m fiber pumped with 80 mW at 979 nm. This compares to 12.7 dBm and 0.71 for a 12 m fiber pumped with 40 mW. Note also that the output is less sensitivity to fiber length for higher pump powers: for 80 mW and this fiber design the gain penalty is <0.1 dB for an uncertainty of $\pm 25\%$ around the optimum fiber length. Fig. 1 also reveals that the magnitude of the gain penalty for pump wavelengths away from 979 nm is significantly reduced at high pump powers. At 80 mW the penalty is <0.5 dB for a pump wavelength range of ± 9 nm about

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