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Stubkjær, Kristian; Mikkelsen, Benny; Djurhuus, Torsten; Storkfelt, Niels; Jørgensen, Carsten; Jepsen, Kim Stokholm; Nielsen, Torben Nørskov; Gliese, Ulrik Bo

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RECENT ADVANCES IN SEMICONDUCTOR OPTICAL AMPLIFIERS AND THEIR APPLICATIONS

K.E. Stubkjaer, B. Mikkelsen, T. Durhuus, N. Storkfelt, C. Joergensen, K. Jepsen, T.N. Nielsen, U. Gliese
Center for Broadband Telecommunications, Electromagnetics Institute,
Technical University of Denmark, DK-2800 Lyngby, Denmark.

Introduction

Two types of optical amplifiers are presently being developed: the erbium doped fiber amplifier and the semiconductor optical amplifier (SOA). The erbium doped fiber amplifier has attracted much attention because of impressive performance, but the SOAs performance is improving and it will also become important for a number of applications. The SOA is in principle simpler than the fiber amplifier but it requires very advanced fabrication technology for ideal performance. It is pumped directly by an electrical current and consists of a single component only, leading to a potential lower price. Another advantage is that it lends itself to opto-electronic integration. Further, SOAs with high gain are available both in the 1.3 and 1.55 μm wavelength regions.

The SOAs major disadvantage and fundamental difference to the fiber amplifier is its nonlinearity due to a short lifetime of the injected carriers. The interaction between gain and carrier density can on the other hand be used in a number of more sophisticated applications where the SOA serves not only as an amplifier, but also as modulator, gate, frequency converter or detector. Here we review recent advances in SOAs and some of their applications.

Progress in semiconductor optical amplifiers

The SOA is in principle a semiconductor laser with reduced facet reflectivities. It is, however, important that the gain is polarization independent which is usually not the case for a laser. Therefore the waveguides in amplifiers must be designed for polarization insensitive gain and at the same time for high coupling efficiencies to optical fibers. Some of these aspects are reviewed in this section.

Polarization sensitivity

Equal gain for TE and TM polarized light requires nearly equal confinement factors for the two polarizations. This is achieved with square shaped buried waveguides [1]-[3]. The cross section of a recently developed Modified Dual Channel Planar Buried Heterostructure (M-DCPBH) waveguide with a width of 0.4 μm and a thickness of 0.3 μm is shown in Fig. 1a [4]. This structure achieves polarization sensitivities of 0.5 dB for an internal gain of 28 dB. It should be noted this high gain is obtained for an injection current of less than 100 mA due to the small cross section of the active guide.

The Ridge Waveguide (RWG) structure with a Separate Confinement Heterostructure (SCH) as shown in Fig. 1b can also achieve a 25 dB internal gain with a polarization sensitivity smaller than 1 dB [5]. Control or

elimination of the stress that is induced by the dielectric coatings is important to realize polarization insensitive devices. This is also the reason for using proton implantation in the M-DCPBH structure.

Facet reflectivities

Low residual facet reflectivities are very important for a low gain ripple, as well as for a low noise figure, intermodulation distortion and crosstalk. For a gain ripple less than 1 dB at 25 dB of internal gain the residual facet

Fig. 1 Cross sections of polarization insensitive SOAs with M-DCPBH structure (A) [4] and RWG SCH structure (B) [5].

reflectivity must be less than $2 \cdot 10^{-4}$. Residual reflectivities of this order can easily be produced, but it is important that they are attained in a large optical bandwidth and are independent of polarization.

Three methods for reduction of the reflectivity are shown in Fig. 2. Double layer AR-coatings have been applied to polarization independent straight facet amplifiers. Reflectivities as low as $7 \cdot 10^{-5}$ have been obtained for both polarizations with $\text{TiO}_2/\text{SiO}_2$ coatings applied to the M-DCPBH structure in Fig. 1a [4].

Fig. 2 Top view of nearly travelling wave SOAs: a) Straight facet amplifier with multilayer AR-coatings, b) Angle facet amplifier with single layer AR-coatings, and c) Buried facet amplifier with single layer AR-coatings.

Angling of the waveguide to the facet normal as shown in Fig. 2b is another approach that is well suited for weakly guided structures. RWG SOAs angled at 7 and 10° and coated with a single layer AR-coating [6] have been fabricated with reflectivities of $3 \cdot 10^{-5}$ and $1 \cdot 10^{-5}$.

Low reflectivities can also be realized with window structures (Fig. 2a) where the active waveguide is terminated in semiconductor material with a matching refractive index [1], [2]. Only a small part of the light coupled through the window sections will be reflected back into the waveguide and residual reflectivities of $2 \cdot 3 \cdot 10^{-4}$ are reported [2].

Packaging

Clearly, a high coupling efficiency is important for a high fiber-to-fiber gain. For the polarization insensitive amplifiers with a thick active layer there is a tradeoff between polarization sensitivity and coupling efficiency since the far field becomes wider and the coupling efficiency small-

er with increasing active layer thickness. The polarization insensitive M-DCPBH structure has coupling efficiencies to tapered lens-ended fibers of 4-5 dB/facet. Both high coupling efficiency and low polarization sensitivity may, however, be realized by tapering the thickness the active layer towards the facets [7]. Similarly the angled facet structure has a tradeoff between coupling efficiency and residual facet reflectivity since the far field becomes increasingly asymmetric with larger facet angles. Coupling efficiencies of 3-4 dB/facet are observed for facet angles of 7-10°. Packaged SOAs with a fiber-to-fiber gain of 17 - 21 dB have been realized [4], [5], [8].

Work on hybrid packaging of SOAs on silicon substrates is now under way to allow for a higher functionality and packaging density. Ultimately, the amplifiers should be monolithically integrated with other components. As examples, integration of lasers and a booster amplifier has been reported [9] and a 2x2 switch array with four integrated SOAs has been demonstrated [10].

Multi quantum well amplifiers

SOAs incorporating multi quantum well (MQW) structures have a number of attractive features compared to bulk devices. Thus, a saturation output power as high as +20 dBm is reported for MQW-SOAs with an unsaturated gain of 7 dB [11]. This should be compared to typical values of +7 dBm for bulk devices. In addition the bandwidth of MQW-SOAs is typically larger than 100 nm.

MQW-SOAs can also exhibit noise figures close to the ideal value of 3 dB, compared to 5-7 dB for bulk devices [12]. An example of measured and theoretically calculated noise figure versus wavelength is seen in Fig. 3. For practical applications, the input coupling losses will increase the effective noise figure by 3-5 dB.

The major drawback of MQW-SOAs is a high polarization sensitivity. This can, however, be reduced or eliminated by strained layers [13].

Fig. 3 Noise figure versus wavelength for 4-well MQW-SOA.

Applications

The SOAs are inherently nonlinear when driven into saturation. Therefore their use as repeaters in multichannel systems will be restricted. They do however have a potential as boosters in transmitters and as preamplifiers in receivers. In the latter case the input signals to the SOAs will be weak and nonlinearities are not a problem. Promising results for a SOA-preamplifier in a 16-channel grating demultiplexer receiver have been reported [14]. Booster and preamplifier applications will especially become attractive as the SOAs are monolithically integrated.

Because of the relatively short lifetime (<1 nsec) of the injected carriers the SOAs may be used for fast signal processing. Recent results for such applications are given in the following.

Gates and switches

One of the most important applications of SOAs could be as gates in high speed switching circuits where the light is controlled by simply modulating the injection current. As the switching time should preferably be comparable or shorter than a bit period the demands are high considering Gb/s data rates. Encouraging results have already been obtained for the M-DCPBH structure (Fig. 1a) which show switching times of 155 and 186 psec for turn-on and turn-off with a driving current of only 100 mA [4].

Optically controlled gates can also be realized. One ex-

Fig. 4 Schematic of optically controlled two-section gate and example of control signal (B) and gated signal (A) (time scale: 200 psec/div).

ample is the two-section SOA shown in Fig. 4. Gating is achieved by saturating the amplifier with light at a wavelength (λ_1) different from the signal wavelength (λ_2). As seen, switching times of ~ 150 psec are achieved [15]. Only -12 dBm of optical power is needed for the control signal since the saturation power of the SOA is low due to the high reflectivity of the cleaved output facet.

Note that the optically controlled gate in Fig. 4 at the same time can be used as a wavelength converter that permits the signal to be shifted up to ~ 50 nm. Electronically controlled 4-electrode wavelength converters, which requires only one optical input, can also be realized [16] but they operate in a more narrow bandwidth.

Phase modulators

SOAs can be used as phase modulators since the refractive index of the material is dependent on the injected carrier concentration, which again depends on the injection current [17]. Typically, a phase modulation of π radians is obtained for a modulation voltage of 1 Volt p-p. The natural modulation bandwidth is 0.5 - 1 GHz and is determined by the carrier lifetime. If larger modulation bandwidths are needed the response of the SOA can be equalized up to 2.5 GHz.

The SOA phase modulators exhibit unwanted amplitude modulation. This can, however, be reduced with two-section SOAs where the two sections are operated with different carrier concentrations and are modulated out of phase [18]. An example of the ratio between phase and amplitude modulation indices (β/m) is seen in Fig. 5 as a function of the modulation power to the back section. Clearly the amplitude modulation can be virtually eliminated. Two-section SOAs may also be used for chirp-free amplitude modulation.

Detection

SOAs can also be used as detectors because the voltage

Fig. 5 Ratio between phase and amplitude modulation for two-section SOA phase modulator.

across the pn-junction (quasi-Fermi levels) depends on the carrier density, which again interacts with the optical input signal [19]. With the SOAs biased to 20 dB of internal gain, responsivities of the order of 250 mV/mW can be obtained. This is sufficient for many applications and makes SOAs attractive as transparent channel drops.

Some advantages can be gained by using a two-section SOA since the first section can amplify the signal while the back section is used for detection. In this case the responsivity can be increased ~30 times compared to the single-section SOA [20].

Conclusion

SOAs are under rapid development to achieve polarization independent gain, low facet reflectivities, good coupling to optical fibers and high saturation power. The packaged SOA can be made compact and possibly inex-

pensive, but its main advantage is the potential for optoelectronic integration.

SOAs may be used as booster and preamplifiers, but in case of multichannel systems attention must be given to the inherent nonlinear behavior that is due to the short lifetime of the injected carrier density. The short lifetime will on the other hand allow SOAs to be used as gates, modulators, detectors and frequency converters for signals with Gbit/s data rates.

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