WAVELENGTH DEMULTIPLEXING HETEROJUNCTION PHOTOTRANSISTOR

Indexing terms: Optical receivers, Demultiplexing, Phototransistors

Experimental and theoretical results on a wavelength demultiplexing receiver composed of an AlGaAs/GaAs heterojunction phototransistor (HPT) integrated within a resonant cavity are reported. A high quality factor cavity was formed using a very thin $In_{0.05}Ga_{0.95}As$ active absorption layer in the collector depletion region of the HPT. Crosstalk attenuations of 15 dB for dual and 12 dB for triple wavelength demultiplexing were demonstrated. The individual HPTs had an optical gain of 500 at the resonant modes. Theoretical calculations predict crosstalk attenuation levels as high as 40 dB with high reflection mirrors on both ends of the cavity.

Wavelength division multiplexing (WDM) is a key technology for increasing the transmission capacity of optical fibre communication systems.[1] A high-speed and high-gain demultiplexing receiver is a crucial part of such a system. For effective use of the available bandwidth, a monolithic multiple wavelength demultiplexing device with a narrow interchannel wavelength spacing and low crosstalk between channels is essential. High performance passive wavelength-selective demultiplexers have been demonstrated.[2,3] These demultiplexers require individual photodetectors for each channel making the monolithic implementation complicated. Using the quantum confined Stark effect,[4] monolithic dual wavelength demultiplexing detectors with low crosstalk (≈ 30 dB) have been demonstrated in *pin* structures.[5] The number of channels is strictly limited to two and the detectors are passive. We report a novel monolithic wavelength demultiplexing device with demultiplexing, detection, and amplification functions at three wavelengths (15 nm spacing).

This demultiplexing device consists of four monolithically integrated resonant cavity enhanced heterojunction phototransistors (RCE-HPT)[6] as shown in Fig. 1. The device structure of the individual RCE-HPT is shown in Fig. 2. The RCE-HPT provides wavelength selective detection functioning as channel discriminators. Such a wavelength selectivity is achieved by the resonant cavity effect of RCE-HPT; i.e., the resonant cavity of length L formed between the buried $\lambda/4$ stack mirror and the epilayer surface enhances the quantum efficiency at resonant wavelengths and rejects the off-resonance wavelengths. By introducing the InGaAs layer, the photosensitivity spectrum extends to longer wavelengths (≥ 900 nm) where the absorption in the base and the heavily doped GaAs collector is negligible. Having a lossless structure, except the thin active region (thickness of d) in the collector, enables the formation of a high quality factor, Q, cavity which strongly enhances the quantum efficiency of the phototransistor at the resonant modes. The resonant wavelength of the cavity can be tuned by recessing the epilayer surface, i.e., changing the cavity length L.[6] In the demultiplexing detector depicted in Fig. 1, four RCE-HPTs with different cavity lengths ($L_1 - L_2$) provide different resonant wavelengths ($\lambda_1 - \lambda_2$).

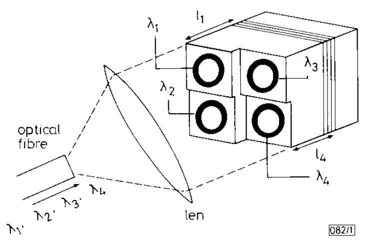

Fig. 1 *Conceptional application for demultiplexing detector composed of four RCE-HPTs with different surface recessing*

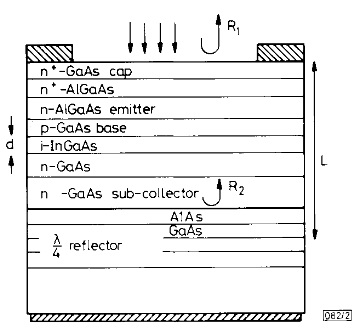

Fig. 2 *Device structure of RCE-HPT*

The resonant cavity is formed between the $\lambda/4$ stack mirror (R_2) below the collector and the semiconductor surface (R_1)

The investigated devices were grown by molecular beam epitaxy (MBE). The growth was initiated with a $0.5\,\mu m$ n^+-GaAs buffer layer. An AlGaAs/GaAs quarter wave stack used as a high reflectivity mirror ($R = 0.9$, centre wavelength ≈ 950 nm) was grown prior to a $0.5\,\mu m$ n^+-subcollector. The collector consisting of $0.4\,\mu m$ n-GaAs ($n = 5 \times 10^{16}\,cm^{-3}$) and $0.1\,\mu m$ undoped $In_{0.05}Ga_{0.95}As$ layers were then grown. This was followed by a p-GaAs base ($0.1\,\mu m$, $p = 5 \times 10^{17}\,cm^{-3}$) and a n-$Al_{0.3}Ga_{0.7}As$ emitter ($0.2\,\mu m$ $n = 5 \times 10^{17}\,cm^{-3}$). A $0.1\,\mu m$ $Al_{0.3}Ga_{0.7}As$ and 500 Å GaAs cap layers (both $n = 5 \times 10^{18}\,cm^{-3}$) were finally grown. Standard photolithographic techniques were employed to integrate four $300\,\mu m$ circular HPTs with $250\,\mu m$ windows. The demultiplexing receiver was formed by selectively recessing the window surfaces of neighbouring devices by 350, 700 and 1050 Å using $NH_4OH : H_2O_2 : H_2O$ (3 : 1 : 150) solution (30 Å/s). The spectral response of the investigated devices was evaluated under monochromatic light illumination.

The free spectral range (FSR) of the RCE-HPT was around 55 nm at 900 nm centre wavelength, and is determined by the cavity length L (FSR $= \lambda^2/(2n_{eff}L)$, n_{eff} is the effective refractive index). Full width at half maximum (FWHM $\Delta\lambda_{1/2}$) was 15 nm with a resulting finesse F of 3.6. The spectral response of individual devices exhibits a peak to valley ratio of 6 : 1 which is slightly less than the theoretical value of 7.7 : 1. A crosstalk attenuation in excess of 15 dB can therefore be obtained for dual wavelength demultiplexing by proper tuning of the channels. In this study, surface recessing was adjusted to obtain three equally spaced modes. The spectral response of device was nearly identical to that of device 1. Fig. 3 shows the spectral responses of units 1–3 under equal illumination and collector emitter bias of 3 V. The crosstalk attenuation for this three way WDM device is roughly 4 : 1 (12 dB). The individual detectors exhibited optical gains as high as 500 and the estimated quantum efficiency was 43% at the resonant modes.

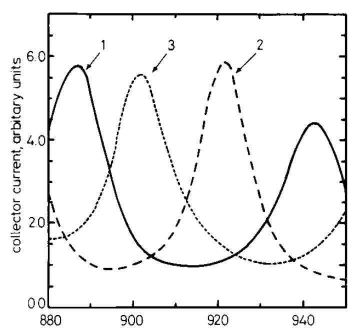

Fig. 3 *Spectral response of three devices with different surface recessing*

The portion of the wavelength spectrum over one free spectral range with minimum crosstalk is shown

Further improvement in the wavelength selectivity of the demultiplexing detector, i.e., higher crosstalk attenuation, can be obtained by increasing the finesse of the cavity. Using the wavelength dependent quantum efficiency equation for the RCE-HPT,[6] an approximate relation between the interchannel crosstalk attenuation, C, finesse and the number of channels can be derived as

$$C \simeq 20 \log \left[1 + \frac{2F}{N}\right] \qquad (N > 3) \quad (1)$$

and finesse is related to mirror reflectivities R_1 and R_2, absorbing layer thickness d, and the absorption coefficient α as

$$F = \frac{\pi(R_1 R_2)^{1/4} e^{-\alpha d/2}}{1 - \sqrt{(R_1 R_2)} e^{-\alpha d}} \quad (2)$$

Examining eqns. 1 and 2, we note that very high crosstalk attenuation can be obtained by increasing the end mirror reflectivities for a thin absorption layer, d.

In this study, the buried mirror is only 10 periods with a corresponding peak reflectivity of $R_2 = 90\%$. Increasing the number of periods to 15 will result in 99% peak reflectivity and enhance the wavelength selectivity. A more drastic improvement can be achieved by increasing the front mirror reflectivity R_1. For example, when $R_1 = 0{\cdot}90$, $R_2 = 0{\cdot}99$, and $\alpha d = 0{\cdot}1$, F is 20, resulting in crosstalk attenuation values of 24 dB and 40 dB for 10 and 4 channel demultiplexing, respectively, and η is 85%. The experimentally demonstrated crosstalk attenuation for $F = 3{\cdot}6$ and $N = 3$ was around 12 dB (can be increased to more than 13 dB by perfect tuning of the channels) and slightly less than the theoretical value of 15·6 dB.

Note that, with increasing F, the wavelength FWHM $\Delta\lambda$ will increase enabling the reduction of channel wavelengths spacing ($F = 20$, gives $\Delta\lambda \leq 3$ nm for the investigated structure). Therefore, with improving wavelength selectivity the number of demultiplexing wavelengths within the same FSR can be increased. Since the incoming beam is to be shared among the channels, the detected photocurrent of individual detectors will increase. The high optical gain of the individual HPTs is therefore crucial. We have demonstrated optical gains as high as 500 on the investigated devices. Even higher phototransistor gains in AlGaAs/GaAs system have been reported.[7] Another important aspect of a optical receiver is the response time. In the AlGaAs/GaAs material system, HPTs with 20 ps detector response time have been demonstrated.[8] The absorbing layer in the investigated device (0·1 μm) is much thinner than typical high speed HPTs. Since the delay time caused by drift of photo-generated carriers is reduced, even better high speed performance can be expected from the present structure. Even for a multi-wavelength demultiplexing system, the device composed of RCE-HPTs represents a high sensitivity and high speed receiver.

We have presented the experimental results on a novel three wavelength demultiplexing detector with high optical gain. A crosstalk attenuation of 15 dB with a FWHM $\Delta\lambda$ of 15 nm was demonstrated. Theoretical calculations predicting very high crosstalk attenuation (40 dB) with extremely small channel spacing ($\Delta\lambda \approx 3$ nm) were presented.

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PHASE MODULATION CHARACTERISTICS OF 1·5 μm STRAINED-LAYER MULTIPLE QUANTUM WELL LASER AMPLIFIERS

Indexing terms: Semiconductor lasers, Phase modulation

Phase modulation characteristics of strained-layer multiple quantum well laser amplifiers were measured to 4 GHz. A phase modulation efficiency of 2·6°/mA was observed at 1 GHz, with a fibre-to-fibre gain of 7 dB and a residual AM modulation of 5%. The characteristics are independent of the input power up to −12 dBm.

Introduction: Semiconductor laser amplifiers (SLAs) can be used as phase modulators through a carrier-induced change of the refractive index. In contrast to electro-optic modulators such as $LiNbO_3$ devices, SLA modulators can provide a net gain to the optical signal and can be made to operate at low driving voltages. The phase modulation (PM) characteristics of double heterostructure bulk SLA modulators were previously measured[1] with a bandwidth of 500 MHz, and their overall performance in system experiments was recently reported.[2] The characteristics of SLA phase modulators can be further enhanced by using multiple quantum well (MQW) active layer structures since their step-like density of states gives wider optical gain bandwidths and higher saturation powers.[3,4]

We report on the performance of a strained-layer MQW (SMQW) SLA used for the first time as a phase modulator. In particular, we studied the PM efficiency characteristics and their dependence on the DC bias current and the optical input power.

Devices: The amplifiers used in this work were realised with an anti-reflection (AR) coating (~0·3% residual reflectivity) on both facets of SMQW planar buried heterostructure lasers.[5] The active layer was composed of three $In_{0.8}Ga_{0.2}As$ wells with a thickness of 20 Å separated by 1·3 μm quaternary barriers. The waveguide was realised with a graded index separate confinement heterostructure. The threshold current for a 750 μm long device was 15 mA before coating. After