High-speed dual-wavelength demultiplexing and detection in a monolithic superlattice *p-i-n* waveguide detector array

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We demonstrate high-speed (1 Gbit/s) dual-wavelength demultiplexing and detection in a monolithic linear array of superlattice *p-i-n* photodetectors in a waveguide configuration. A crosstalk attenuation of 28 dB was achieved between two digital transmission channels with an interchannel wavelength spacing of 30 nm. The device performance is a result of an enhanced electroabsorption due to the quantum-confined Stark effect in the superlattice *p-i-n* diodes.

Wavelength division multiplexing is an attractive technique for increasing the transmission capacity in fiber-optical communication systems by utilizing the low-loss characteristics of optical fibers over a wide wavelength region.[1] In such a system the optical demultiplexer is a key device. For effective use of the fiber bandwidth and for error-free operation, a narrow interchannel wavelength spacing and low crosstalk between channels are necessary. Passive wavelength-selective demultiplexers of both the angularly dispersive type[2] and the dielectric thin-film filter type[3] have successfully been used. However, these demultiplexers require critical alignment of several optical components. In addition, one photodetector per channel is needed to detect the demultiplexed signals. Active wavelength-selective demultiplexers, which perform both demultiplexing and detection, are important since they simplify system configurations. Monolithic multiwavelength photodetectors have been studied previously, but they suffer from a poor wavelength selectivity or an unsatisfactory degree of crosstalk suppression.[4-7]

In this letter, we present results on a high-speed dual-wavelength demultiplexing experiment using a monolithic linear array of superlattice *p-i-n* photodetectors in a waveguide configuration. The detectors can be tuned to different wavelengths using the electroabsorption effect, and wavelength-multiplexed optical signals can be demultiplexed directly into different electrical channels.[4,5] In our device, an improved wavelength selectivity and an increased crosstalk attenuation are achieved as a result of an enhanced electroabsorption in the superlattice *p-i-n* diodes that constitute the detector.

The device structure is schematically shown in Fig. 1. The epitaxial layers were grown by molecular beam epitaxy on an n^+-GaAs substrate and consist of a *p-i-n* doped AlGaAs/GaAs heterostructure with a superlattice intrinsic region, surrounded by thin undoped graded superlattice buffers to reduce the background doping concentration. The structure is described in greater detail elsewhere.[8] An array of separate *p-i-n* photodiodes was defined by proton implantation (120 keV, 5×10^{14} cm^{-2}), which provides electrical isolation (>1 GΩ) and reduces the capacitance of the individual diodes to 0.7 pF. After metallization and lapping the chip was cleaved into individual two-element edge detectors and mounted for high-speed operation. The final capacitance of each diode was $\sim$0.9 pF at the operating bias, which implies an *RC* time constant limited impulse response in the 100 ps range. This detector geometry provides optical waveguiding perpendicular to the layers, and is compatible with integrated optoelectronics.

The wavelength selectivity is based on the quantum-confined Stark effect.[9] When the electric field is increased in the superlattice intrinsic region by increasing the applied reverse bias over the *p-i-n* diode, a redshift of the excitonic absorption energies is observed. This is due to an electric field induced decrease in the confinement energies of the quantized states in the conduction and valence bands. The spectral response of a superlattice *p-i-n* photodetector for different applied reverse biases, when illuminated with monochromatic light, is shown in Fig. 2. The two peaks at the band edge correspond to the first quantized heavy hole-to-electron and light hole-to-electron excitons. A large shift of the near-band-edge absorption to lower energies can be seen with increasing reverse bias, and initially transparent spectral regions become highly absorbing. This shift is larger than the Franz–Keldysh effect seen in bulk material. The sharpness of the absorption edge is also preserved because the band discontinuities prevent ionization of the excitons

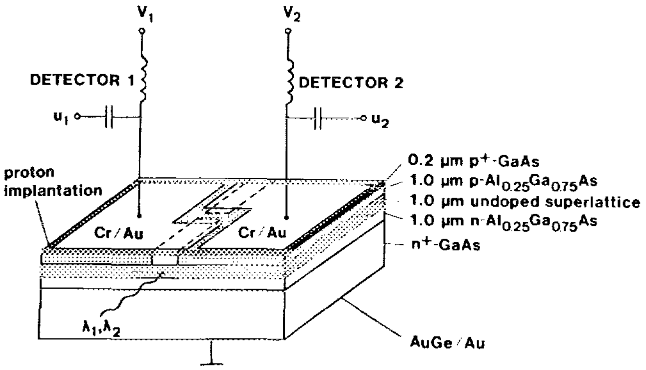

FIG. 1. Schematic view of the two-wavelength demultiplexing superlattice *p-i-n* waveguide detector. The superlattice consists of 100-Å GaAs wells and 50-Å $Al_{0.25}Ga_{0.75}As$ barriers and is surrounded by undoped graded superlattice buffers, each with a total thickness of 385 Å. The detectors are 20 μm wide, the lengths of detectors 1 and 2 are 20 and 50 μm, respectively, and the separation is 10 μm.

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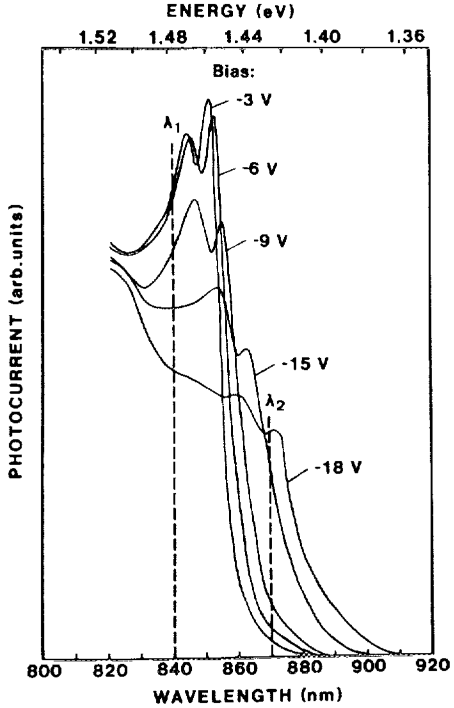

FIG. 2. Photocurrent spectra under different applied reverse biases. The dashed lines indicate the wavelengths (λ_1 and λ_2) used in the demultiplexing experiment.

even at high electric fields. This effect has recently been investigated for optical modulators,[10,11] self-electro-optic effect devices,[12] tunable photodetectors,[8,13] and actively Q-switched quantum well lasers.[14] The spectral and temporal characteristics of the superlattice *p-i-n* photodetectors used here have recently been investigated by us.[8] A temporal response, full width at half-maximum (FWHM), in the 100-ps range was observed without any indication of carrier trapping at the interfaces. In the present demultiplexing experiment, the second detector along the waveguide is more reverse biased than the first, thus absorbing photons with energies just below the absorption edge of the first detector. Appropriately chosen incident optical wavelengths will therefore be absorbed by different detectors.

The experimental setup for the dual-wavelength demultiplexing experiment is shown in Fig. 3. The outputs from two AlGaAs lasers operating at 840 nm (λ_1) and 870 nm(λ_2) were combined in a beamsplitter and focused onto the cleaved edge of the two-wavelength detector. The choice of wavelengths was determined by the lasers available in our laboratory. A monochromator was used to observe the lasing wavelengths and the longitudinal mode spectra. The lasers were biased at threshold and modulated with 80 ps (FWHM) electrical pulses to produce short optical pulses at a repetition rate of 1 Gbit/s and 500 Mbit/s, respectively. Figure 4 shows the output signals (u_1 and u_2) when detector 1 and detector 2 were reverse biased at 5 V (V_1) and 15 V (V_2), respectively. The impulse response was 100 ps (FWHM), determined by the laser pulse width and the detector *RC* time constant. From the experimental data we determine the electrical crosstalk attenuation to be 28 dB at 870 nm and more than 30 dB at 840 nm. The wavelengths used in the demultiplexing experiment are indicated by the dashed lines in Fig. 2. From the photocurrent spectra we infer that the interchannel wavelength spacing could be reduced to 20 nm ($\lambda_1 = 850$ nm and $\lambda_2 = 870$ nm) without decreasing the crosstalk attenuation. The responsivities for detectors 1 and 2 at the operating wavelengths and biases were measured to be 0.20 and 0.12 A/W, respectively. This corresponds to quantum efficiencies of 30% and 17%, and includes losses due to reflection, coupling, and scattering. An improvement in responsivity could be achieved by antireflection coating the cleaved edge and by introducing waveguiding parallel to the epitaxial layers. Furthermore, by optimizing the lengths of the individual detectors, and by using dynamic single-mode lasers of appropriate wavelengths, we believe that three channels, with an individual wavelength separation of 10 nm, could be demultiplexed with a crosstalk attenuation of at least 20 dB.

In conclusion, we have, for the first time, demonstrated active dual-wavelength demultiplexing and detection at Gbit/s data rates. A crosstalk attenuation as high as 28 dB was achieved with an interchannel wavelength spacing of 30 nm. The device has a potential for demultiplexing a larger number of wavelength-multiplexed optical channels with a satisfactory degree of crosstalk suppression.

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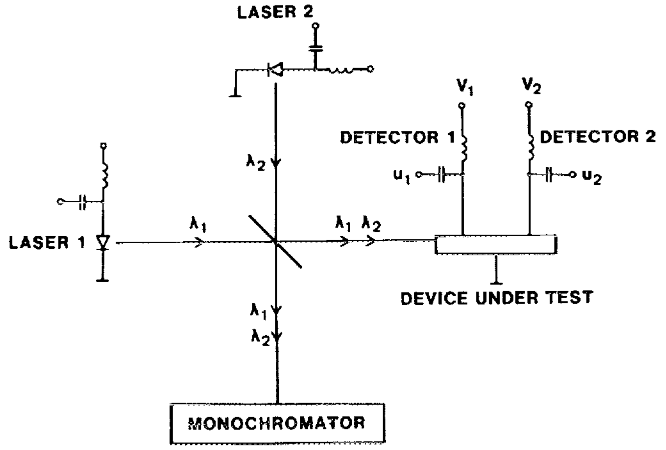

FIG. 3. Experimental setup for the demultiplexing experiment.

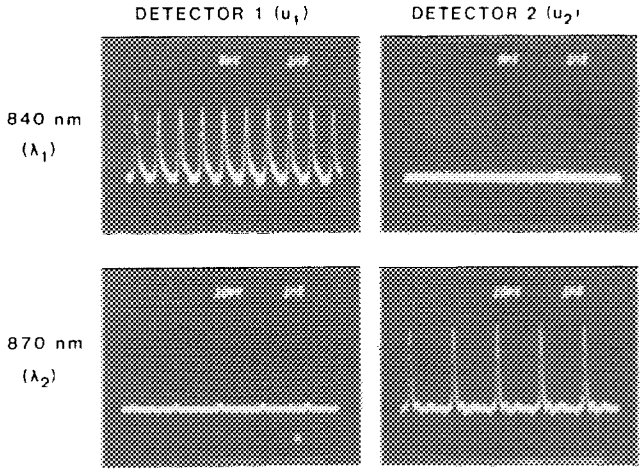

FIG. 4. Results of the dual-wavelength demultiplexing experiment. Detector 1 and detector 2 were reverse biased at 5 V (V_1) and 15 V (V_2), respectively.

bonding the device. The work at Chalmers was sponsored by the National Swedish Board for Technical Development. The Caltech effort was supported by the Office of Naval Research and the ITT Corporation.

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