Nonlinear effects in coplanar GaAs/InGaAs strained-layer superlattice directional couplers

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We report on the performance characteristics of InGaAs/GaAs strained-layer superlattice coplanar ridge-type directional couplers realized by molecular beam epitaxy. The measured power transfer characteristics with 1.15 μm incident photoexcitation demonstrate nonlinear coupling due to absorption associated with the tails of the excitonic resonances in the quantum wells. From a theoretical fit of the measured data, the nonlinear refractive index coefficient, n_2, of the multiquantum well is found to be 2.25×10^{-7} cm^2/W. This agrees very well with a value of $n_2 = 1.9\times10^{-7}$ cm^2/W obtained independently on the same material from interferometric measurements.

Optical directional couplers are important elements in optoelectronic integrated circuits (OEIC's) using a guided-wave scheme. Waveguide couplers can serve as switching elements.[1,2] In this letter we report the coupling characteristics of coplanar GaAs/InGaAs strained-layer superlattice (SLS) waveguide couplers. Nonlinear coupling behavior is seen in the SLS structures. From a theoretical fit to the data, a value for the nonlinear refractive index is derived. The latter parameter has been measured in the same materials using a Mach–Zender interferometer.

The structures were grown by molecular beam epitaxy (MBE) on GaAs substrates. The schematics of the grown layers and structures for the coplanar coupler are shown in Fig. 1. In the measured room-temperature absorption spectrum of the InGaAs/GaAs SLS, the energy position of the heavy-hole excitonic transitions is 1.1198 eV, which is ~40 meV higher than the photon energy of the experimental 1.15-μm source used in the present measurements. Single-mode waveguides were delineated by using photolithography and ion-milling techniques.

Quantitative measurements on the coupling characteristics were made with the input guide end fired by a 2–3 μm collimated and focused beam from the 1.15-μm He-Ne laser. The incident light power was estimated to be 750–800 μW and its plane of polarization was TE-like, i.e., parallel to the layers of the heterostructures. The output from the incident and coupled guides for various coupling lengths was measured by a liquid-N_2-cooled Ge photodetector and viewed on a TV monitor via an infrared camera. The power distribution in the input and coupled guides of the coplanar structure for various coupling lengths is shown in Fig. 2. It is interesting to note that, contrary to the expected behavior of the linear couplers, lesser power is transferred to the coupled guide for small coupling lengths. We believe this is due to the nonlinear backcoupling or switching of power from the coupled to the input guide for these short coupling lengths resulting principally from a local change of the refractive index.[3–5] We estimate that a refractive index change of ~0.01 in the SLS is required to produce this effect and that it is easily achieved with the input power density available in the experiments.

In order to verify the nonlinear effect, we have calculated the coupling characteristics taking into account lossy guides coupled by a nonlinear medium. The intensity-dependent absorption coefficient and refractive index are given by

$$\alpha(I) = \alpha_0 + \alpha_2 I, \tag{1a}$$

$$n(I) = n_0 + n_2 I, \tag{1b}$$

where α and n are the absorption coefficient and refractive index of the nonlinear medium. Screening of the Coulomb interactions and band filling effects under high-excitation levels gives rise to a quenching of the exciton resonance and a change in α or n. For switching applications, where transient conditions are operative, α can be obtained from a solution of the rate equation for excess carriers generated by photoexcitation, as outlined by Wherrett.[6]

One can express

$$n_2 = F\alpha, \tag{2}$$

and this dependence can be nonlinear for large α, as experimentally found by Li Kam Wa *et al.*[3] The coupled-mode equations for the propagation of power in lossy nonlinear directional couplers are then

$$\frac{da_1}{dz} = i\beta a_1 - \frac{\alpha}{2} a_1 + iCa_2 - i\alpha F |a_1|^2 a_1, \tag{3a}$$

$$\frac{da_2}{dz} = i\beta a_2 - \frac{\alpha}{2} a_2 + iCa_1 - i\alpha F |a_2|^2 a_2, \tag{3b}$$

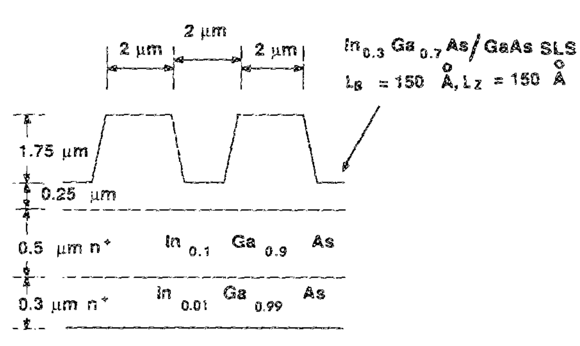

FIG. 1. Structure of coplanar waveguide coupler with $In_{0.3}Ga_{0.7}As$/GaAs strained-layer superlattice guiding and coupling regions realized by molecular beam epitaxy.

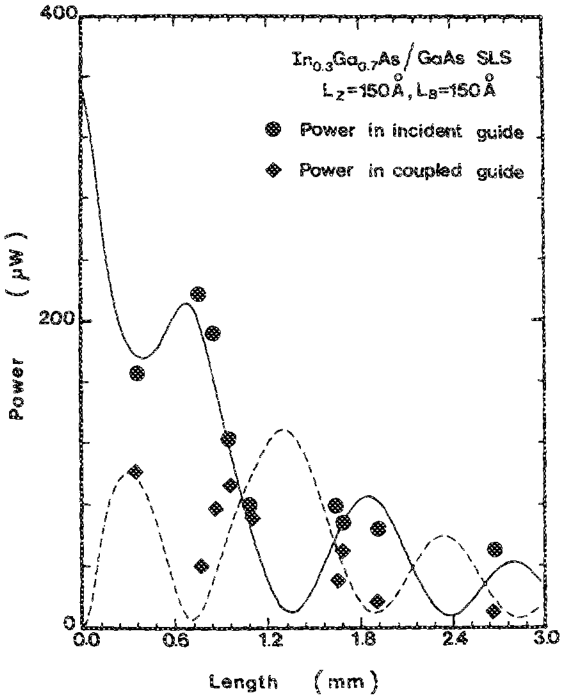

FIG. 2. Power transfer characteristics of the coplanar strained-layer superlattice (SLS) waveguide coupler. The data for different coupling lengths were obtained by the cutback method. The solid and dashed curves are calculated data for the input and coupled guides, respectively.

where a_1 and a_2 are the amplitudes of the two waves, expressed as

$$a_1 = A_1 e^{-(\alpha/2)z + ikz}, \tag{4a}$$

$$a_2 = A_2 e^{-(\alpha/2)z + ikz}, \tag{4b}$$

and $C = \pi/2L_C$, where L_C is the critical coupling length (100% power transfer).

Equations (3a) and (3b) have been numerically solved using the Runge–Kutta technique, to fit the experimental data. The solid and dashed lines in Fig. 2 are the calculated powers in the two guides obtained for $n_2 = 2.25\times 10^{-7}$ cm^2/W, $\alpha = 30$ cm^{-1}, and $L_C = 0.4$ mm.

Single waveguides typically 1.1 mm long and of the same dimensions as the coupler were fabricated with the SLS material. A Mach–Zender interferometer was constructed with the guide placed in one arm, as shown in Fig. 3. The 1.15-μm light in this path was guided in the SLS region. The interference fringes observed due to the interference effect are shown in the inset of Fig. 4. A shift of the fringes was observed and recorded for increasing light intensity. The corresponding phase shifts were also calculated. The variation of the phase shift with input power is shown in Fig. 4. Assuming a linear dependence of the phase shift on input power[3] one can express the nonlinear refractive index in the SLS as

$$n_2 = \frac{\Delta\phi}{P_i}\left[\frac{2\pi}{\lambda_0 A}\left(\frac{1-\exp(-\alpha l_z)}{\alpha}\right)\right]^{-1}, \tag{5}$$

where $\Delta\phi$ is the relative phase shift, P_i is the input power, A is the guide cross section, l_z is the length of the guide, and λ_0 is the free-space wavelength of the incident light. Using Eq.

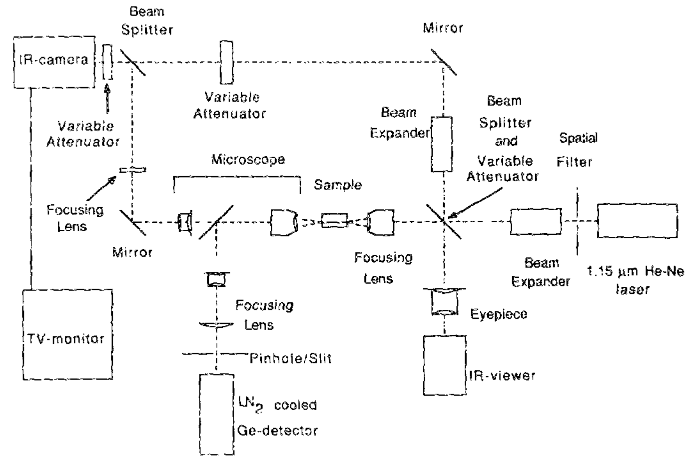

FIG. 3. Schematic of the Mach–Zender interferometer for measurement of nonlinear refractive index. A 25-μm pin hole was used to detect the output light.

(5) for the data in Fig. 4, a value of $n_2 = 1.9\times 10^{-7}$ cm^2/W is derived, which is in good agreement with that obtained from the coupled power data.

A comment should also be made here about the possible refractive index change due to thermal effects. It has been recently established by Li Kam Wa *et al.*[3] that thermal heating of similar GaAs/AlGaAs multiple quantum well (MQW) couplers essentially moves the fringes in the opposite direction and results in a positive nonlinear refractive index coefficient. This sign of change would not show the nonlinear coupling observed by Li Kam Wa *et al.*[3] or by us. It may, therefore, be concluded that the nonlinearity observed by us is predominantly due to high-speed nonlinear excitonic effects in the MQW.

To our knowledge this is the first demonstration of nonlinear coupling behavior in SLS material. The effect can be

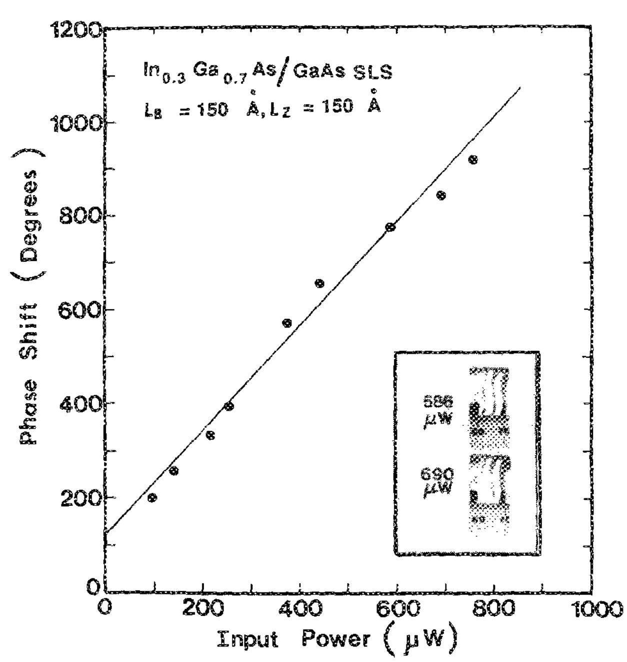

FIG. 4. Measured variation of phase shift with power incident on the SLS guide in one arm of a Mach–Zender interferometer. The inset shows the observed fringes at the output for (a) 586 μW and (b) 690 μW.

seen more clearly, and utilized for photonic switching with higher light intensities, and these experiments are in progress in our laboratories.

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