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An Optically-Triggered Semiconductor Switch for High Power Laser Beams

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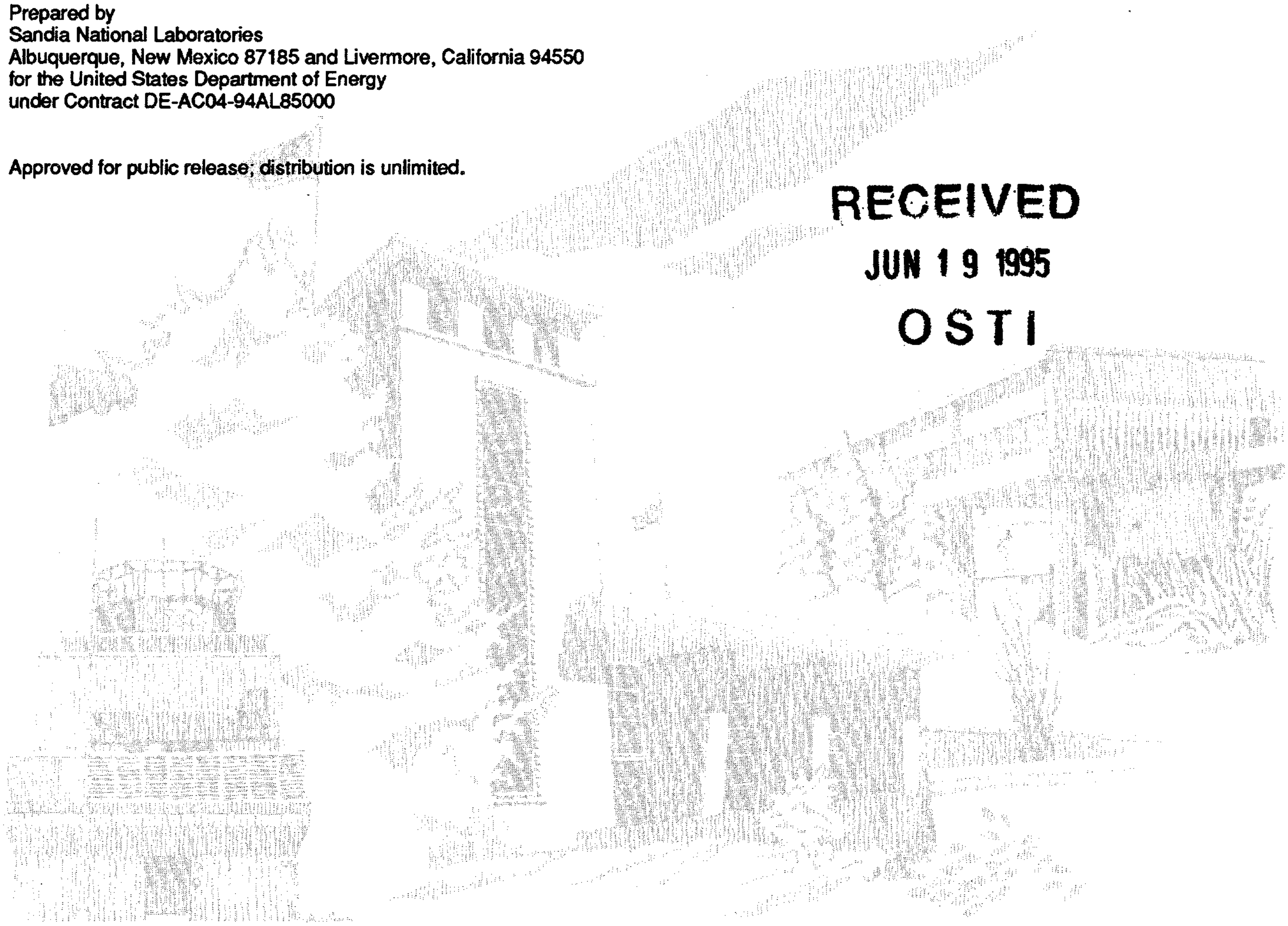

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An Optically-Triggered Semiconductor Switch for High Power Laser Beams

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Abstract

The work involves research leading to an optically-triggered switch for a high power laser pulse. The switch uses a semiconductor heterostructure whose optical properties are modified by a low power laser trigger such as a laser diode. Potential applications include optical control of pulsed power systems, control of medical lasers and implementation of security features in optical warhead architectures.

Acknowledgement

The authors thank Dr. M. Peirra and Professor S. Koch from the University of Arizona, and Dr. Victor Esche from the U. S. Air Force for collaborations on theoretical and experimental aspects of the problem.

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An Optically-Triggered Semiconductor Switch for High Power Laser Beams

Introduction

The safety and security of a nuclear weapon may be enhanced by using optical signals in applications that presently require electrical signals. An advantage is greatly increased electrical isolation. In addition, if one uses the output of a high-power pulsed laser, the optical signal properties is sufficiently unique so as to be irreproducible by any natural phenomenon. The present effort to demonstrate direct optical initiation (DOI) of nuclear weapons by a pulsed Neodymium laser is based on these premises. An important addition to the DOI architecture is an enabling switch for the laser pulse. The state of the art in optical switch technology for high-power laser beams limits one to optomechanical switches. Optomechanical devices are complicated, slow and sensitive to alignment errors, shock and vibration.

This report describes an investigation on the feasibility of an all-optical switch. Our idea is based on the carrier-induced refractive changes present in a semiconductor heterostructure. This switch deflects a high power laser beam when it is triggered by a low-power optical signal. The investigation was carried out during FY 1992-1993 at Sandia as part of a Laboratory Directed Research and Development project.

Background

The general idea for the proposed switch is depicted in Fig. 1. The device is a solid, monolithic structure consisting of an AlGaAs layer grown epitaxially on a GaAs crystal. There are two modes of operation: one with essentially all of the high-energy laser beam transmitting through the switch; the other with essentially all of the high-energy laser beam undergoing total internal reflection at the interface. Total internal reflection is possible because the refractive index of AlGaAs is lower than that of GaAs. The sine of the critical angle for total internal reflection is the ratio of the lower (incident) refractive index to the higher (outer) refractive index. The switching action is based on the carrier density dependence of the refractive index in a semiconductor. Using a laser diode, we can generate carriers in either the GaAs or the AlGaAs layers. This changes the relative refractive index at the wavelength of the high-energy laser beam, at the interface between the two materials, resulting in a change of the critical angle for total internal reflection. With the proper geometry, and depending on the laser diode wavelength, a normally transmitted high energy laser beam may be switched to being totally internally reflected or vice versa.

The success of our idea depends critically on achieving a sufficiently large carrier-induced refractive index difference between the AlGaAs and GaAs layers. Data exist for the near-bandgap carrier-induced refractive index changes in GaAs and AlGaAs. However, little work has been done at *1.06μm*, which is the wavelength of interest to DOI. In order to obtain an accurate estimation of the feasibility of our scheme, it is necessary to fill this knowledge gap. A model for the nonlinear interaction of laser radiation with semiconductors was developed The Coulomb interaction is treated fully because the bleaching of the well-resolved excitons dominate the nonlinearities at the low densities expected for the switch. This theory was first applied to bulk AlGaAs-GaAs layers. Due to the large near-bandgap nonlinearities observed in quantum well structures, we extended our theory to include the investigation of quantum well and strained quantum-well structures.

Theory

The Maxwell-semiconductor-Bloch equations (MSBE), give a consistent description of the optical response of a semiconductor medium in the presence of many-body Coulomb effects. They consist of two sets of equations coupled to each other: the semiconductor-Bloch-equations (SBE) and the reduced wave equation (RWE).[1-3] The latter, which describes the propagation of the light field envelope, E, is given by

$$\frac{\partial E}{\partial \xi} = \frac{i\mu_0\omega_0^2}{k_0 V} \sum_{\vec{q}} \mu_{\vec{q}} P_{\vec{q}}(\eta, \xi), \quad (1)$$

where μ_0 is the permeability, μ_q is the dipole matrix element, ω_0 *and* k_0 are the optical carrier frequency and wavevector, V is the volume of the active region, $\eta = t - z/c$ and $\xi = z$ are the retarded time and space coordinates obtained by using a traveling frame at the group velocity c of the pulse, and the summation is over all electron-hole momenta. The source term on the right hand side is determined by the total polarization $\Sigma_q \mu_q P_q$, where each polarization function P_q with electron wave number $\boldsymbol{q}$ obeys the SBE:

$$\frac{\partial P_q}{\partial \eta} = -i(\omega_q - \omega_0)P_q - i\Omega_q(f_q^e + f_q^h - 1) + \frac{\partial P_q}{\partial \eta}\Big|_{coll}, \quad (2)$$

$$\frac{\partial f_q^e}{\partial \eta} = i(P_q^* \Omega_q + c.c.) + \frac{\partial f_q^e}{\partial \eta}|_{coll}, \tag{3}$$

and

$$\frac{\partial f_q^h}{\partial \eta} = i(P_q^* \Omega_q + c.c.) + \frac{\partial f_q^h}{\partial \eta}|_{coll}, \tag{4}$$

where Eqs. (3) and (4) are the equations of motion for the electron and hole population distributions. In Eqs. (2)-(4), the Rabi frequency of the light is

$$\Omega_q = \frac{1}{\hbar}(\mu_q E + \Sigma_q V_{q-q'} P_{q'}). \tag{5}$$

It is renormalized by Coulomb many-body terms, where V_q, the screened Coulomb potential in Fourier space, is treated in a quasi-statistical screening model.[4] Also,

$$\hbar\omega_q = \hbar\omega_{q,0} + \Delta\varepsilon_{SX} + \Delta\varepsilon_{CH} \tag{5}$$

is the renormalized transition energy, where $\hbar\omega_{q,0}$ is the single particle transition energy, $\Delta\varepsilon_{CH}$ and $\Delta\varepsilon_{SX}$ are the screened exchange and Coulomb-hole contributions to the bandgap renormalization. Besides the renormalized Rabi frequency and shifted bandgap energy, which result from a time dependent Hartree-Fock approximation in the equations of motion, carrier-carrier collisions tend to drive the nonequilibrium population distributions into quasi-equilibrium Fermi-functions and yield optical dephasing. The collision terms, $\partial P_q / \partial\eta|_{coll}$, $\partial f_q^e / \partial\eta|_{coll}$ and $\partial f_q^h / \partial\eta|_{coll}$ in our treatment are approximated in the relaxation rate approximation using time constants of 100 fs.[5]

For bulk semiconductor layers, we assume parabolic bandstructures for the single-particle electron and hole energies. In the case of quantum well structures, we assume a parabolic bandstructure for the single-particle electron energy and use Luttinger theory[6] to compute the single-particle hole energy. The bandstructure calculation also gives the dipole matrix element, μ_q .[7] Input parameters to the calculation are the transition linewidth, γ, the bulk material Luttinger parameters, unrenormalized bandgaps, energy offsets, deformation potentials and lattice constants.[8,9] Investigations based on MSBE predict many-body effects in infrared III-V lasers that are verified in experiments.[6]

Carrier-Induced Refractive Index Change

We begin with computing the refractive index change in thick (bulk) semiconductor layers. Figure 2 summarizes the results obtained by solving the MSBE for a bulk GaAs layer. It shows a refractive index change of $\delta n = -0.003$ with a carrier density of $N = 10^{18} cm^{-3}$. Back of the envelope calculations indicate that operation of our switch is very difficult with this small a refractive index change. The onset of total internal reflection becomes strongly dependent on beam divergence and temperature. While as much as $\delta n = -0.008$ is possible with $N = 2 \times 10^{18} cm^{-3}$, creating such a high population is difficult and can possibly lead to the appearance of gain at the trigger signal wavelength.

A larger carrier-induced refractive index change may be possible by exploiting the sizable near-bandgap nonlinearities of semiconductor quantum wells. InGaAs compounds are good candidates for our purpose because of their bandgap energy. Current epitaxial growth techniques allow the growth of high quality InGaAs-InP and InGaAs-GaAs quantum wells. However, in order to reach the *1.06μm* wavelength range, the Indium concentration required is below the lattice matching condition with InP barriers. In this case the quantum wells are subjected to tensile strain, which strongly couples the heavy and light hole bands resulting in higher carrier density for achieving the necessary refractive index change. On the other hand, InGaAs-GaAs quantum wells are under compressive strain for the *1.06μm* wavelength. The compressive strain uncouples the heavy and light hole bands, thus reducing the necessary carrier density and consequently the optical trigger power.

Figure 3 depicts the free-carrier bandgap of InGaAs-GaAs quantum wells as a function of Indium concentration for different quantum well widths. From the figure and taking into account that the actual absorption edge at low carrier densities is red-shifted by the lowest subband heavy hole exciton binding energy, a 10nm $In_{0.28}Ga_{0.72}As$-GaAs quantum well is a good candidate for our switch.

Figure 4 illustrates the evolution of the optical absorption spectra and corresponding refractive index changes as we increase the carrier density (by increasing the trigger signal) in the system. We see that there is substantial refractive index change at *1.06μm*, and that at this wavelength, the excitonic absorption is reasonably low.

Figure 5 depicts the dependence of the absorption and refractive index change at *1.06μm* on quantum well width and Indium concentration. The carrier density is $N = 5 \times 10^{17} cm^{-3}$. Note that both the absorption peak value and the maximum value of the refractive index change increase as the well width is reduced due to the increased quantum confinement. Furthermore, higher concentrations of Indium are required to compensate for the quantum-confinement induced blue shift of the absorption line.

For a given quantum well width, Figs. 3 to 5 allow us to determine the Indium concentration that will maximize the refractive index change at *1.06μm*. The combinations are (quantum well width in nm, indium concentration): (17.5, 0.263), (15, 0.267), (12.5, 0.274), (10, 0.297), (7.5, 0.306), and (5, 0.353). Figure 6 shows the variation in the absorption and refractive index change as a function of carrier density for these combinations.

Switch Design

The basic design of a switching interface as shown in Fig. 1 was investigated using nominal index of refraction values for GaAs and AlGaAs (with 30% Al concentration). The refractive indices of InGaAs and InGaAs quantum well structures are slightly different, but the values are not as well known and the changes in critical angle and Fresnel reflection coefficients will be insignificant to the analysis. The index of refraction for GaAs at 1.06 mm is 3.49 and is 3.33 for 30 % AlGaAs. The resulting critical angle at the interface between the two materials is 72.59 degrees. A decrease in the index of GaAs of -0.003 changes the critical angle to 72.74 degrees. A decrease of -0.008 gives a critical angle of 73.01 degrees. The theoretical predictions of the previous section therefore indicate that the critical angle can be changed by as much as 0.4 degrees. This is a small amount. However, if the beam was composed of nearly perfectly collimated plane waves of uniform intensity, switching would occur for a beam incident at an angle between the two extreme values of the critical angle. A beam incident at 72.8 degrees would be totally reflected by the interface with unexcited GaAs (actually an InGaAs quantum well structure). With sufficient carrier excitation to achieve a refractive index change of -0.008, the beam will be partially transmitted through the interface. The amount of transmission is determined by the Fresnel reflection loss at the interface. For the example discussed here, the reflection at the interface, for the 1.06 mm beam incident near the critical angle, would be approximately 44% for p-polarized light and 47% for s-polarized light. These losses are a significant factor limiting the contrast achievable by the switch, as the reflected beam will exit in the same direction and manner as the beam undergoing total internal reflection.

While the switch configuration shown in Fig. 1 is useful for illustrating our idea, it is not a practical switch structure. The high index of refraction of the materials under discussion makes it very difficult to couple beams with high efficiency near the critical angle for the semiconductor interface. Use of surface grating structures to couple the 1.06

μm beam into the switch at the proper angles seems the most promising approach, as shown in Fig. 7. These coupling gratings will not be 100% efficient, so the process of coupling the 1.06 μm beam into and out of the switch into air or another low-index medium will have additional losses. The pump beam for producing carriers can be normal incidence, and can be coupled with good efficiency using appropriate coatings.

Conclusion

For this LDRD project, we began by investigating the optical properties of bulk GaAs and AlGaAs as potential switch materials. An existing microscopic theory was used to compute the carrier-induced refractive index change. During the course of our studies, we realized that the switching properties of semiconductors may be enhanced by quantum confinement and strain. We extended the microscopic theory to include valence band mixing effects necessary for the treatment of strained quantum well structures. This improved theory was used in a parametric study of possible quantum well structures for implementing our switch concept.

The predicted values for the refractive index changes possible for carrier excitation in the semiconductor materials studied indicate an all-optical switch may be possible. There are a number of factors to be considered before predicting that such a switch is practically possible. As mentioned earlier, the analysis assumes nearly perfect beam quality for the pump and switched beams. This is not the case with sources currently available for a demonstration. The analysis ignores two-photon effects from the intense 1.06 μm beam which may tend to cause self-switching. The contrast and efficiency of the switch are limited by a number of factors which are also very dependent on the exact implementation of the switch that was attempted. With these considerations, we conclude that an optically-triggered semiconductor switch using the total internal reflection mechanism is not practical at this time.

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Appendix, LDRD Summary

Refereed publications resulting for the work:

W. Chow, M. Pereira and S. Koch, 'A many-body treatment on the modulation response in a strained quantum well semiconductor laser medium,' Appl. Phys. Lett. **61**, 758 (1992).

M. Pereira, S. Koch and W. Chow, 'Effects of strain and Coulomb interaction on the linewidth enhancement in quantum well lasers,' JOSA **B10**, 765 (1993).

P. Ru, J. V. Moloney, R. Indik, S. W. Koch and W. Chow, 'Microscopic modelling of bulk and quantum well GaAs-based semiconductor lasers,' Optical and Quantum Electronics **25**, 675 (1993).

W. Chow, 'Quantum confinement and strain effects in nonlinear semiconductor gain media,' invited paper, 184th Meeting, The Electrochemical Society, New Orleans, Oct. 10-15, 1993.

S. Koch and W. Chow, 'Microscopic Theory and Modelling of Semiconductors and Semiconductor Lasers,' chapter in Trends in Optical Engineering, J. Menon, ed., Research Trends, India (1994).

All other reports and publications from the work: 0

Number of patent disclosures: 0

Number of patent applications: 0

Number of patents: 0

Number of copyrights: 0

Number of students: 1

Number of post docs: 0

Number of permanent technical or scientific staff: 0

Number of awards (and their names): 0

Number of new non-LDRD funded projects and their amounts: 0

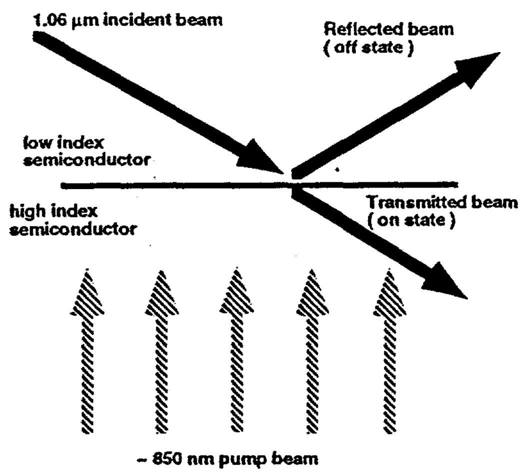

Figure 1. Proposed semiconductor optical switch. In the absence of a low-power incident beam from a semiconductor laser diode, the high power *1.06μm* laser beam experiences total internal refractive at the GaAs-AlGaAs interface.

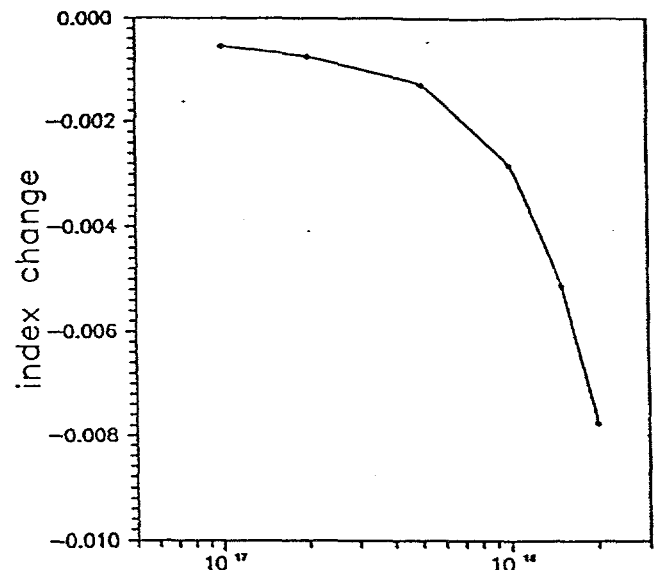

Figure 2. Index change at 1.06μm wavelength vs carrier density in bulk GaAs. The temperature is 300K and the density is in units of cm^{-3}.

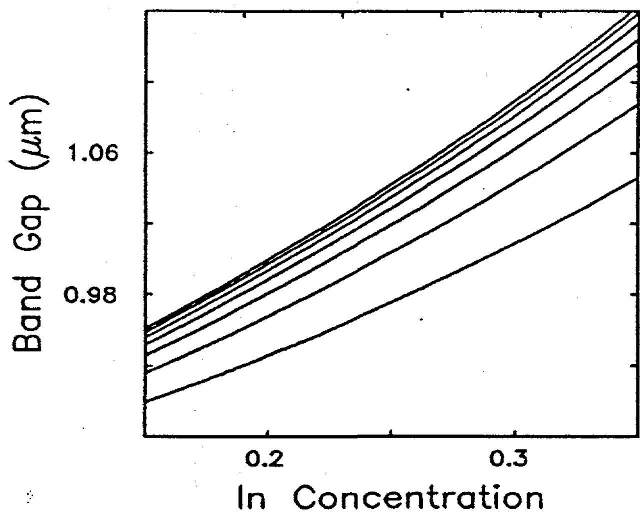

Figure 3. Unexcited bandgap energy for InGaAs-GaAs quantum well as a function of Indium concentration. The temperature is 300K and the well widths are (top to bottom) 5nm, 7.5nm, 10nm, 12.5nm, 15nm, 17.5nm and 20nm.

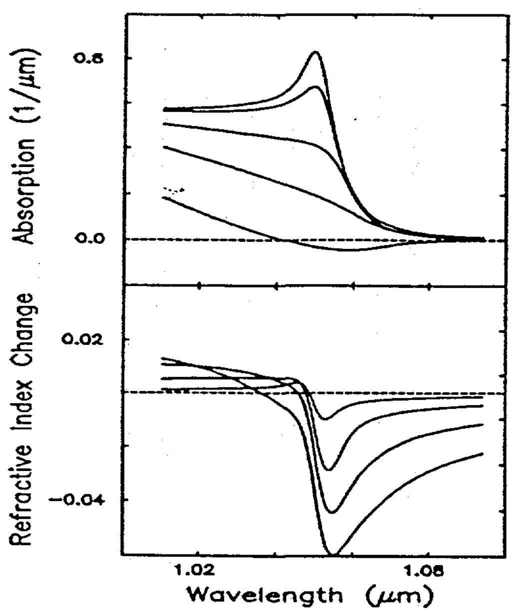

Figure 4. Optical absorption (top) and refractive index change (bottom) vs. carrier density for a 10nm $In_{0.28}Ga_{0.72}As$-GaAs quantum well at 300K. The carrier densities are (top to bottom) N = 0, $5x10^{16}cm^{-3}$, $2x10^{17}cm^{-3}$, $5x10^{17}cm^{-3}$ and $10^{18}cm^{-3}$.

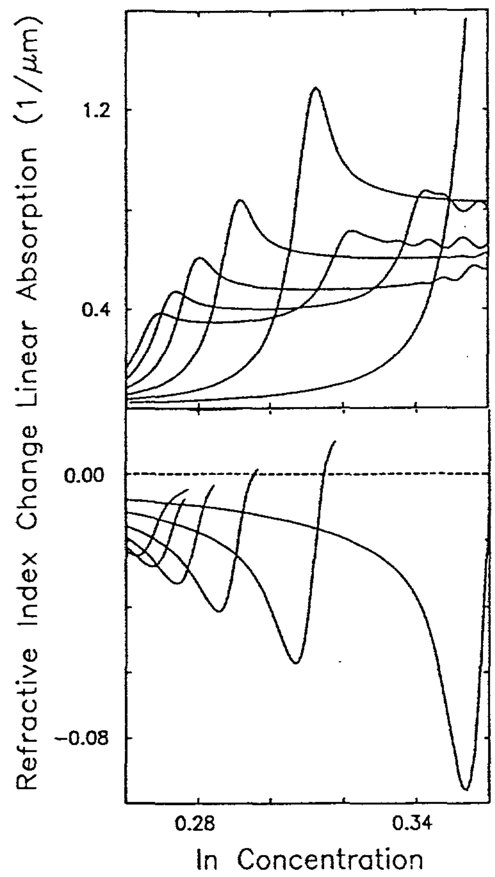

Figure 5. Optical absorption (top) and refractive index change (bottom) at 1.06μm vs. Indium concentration, for a carrier density of $N = 5x10^{17}cm^{-3}$ and 300K. The quantum well widths are (from left to right) 17.5nm, 15nm, 12.5nm, 10nm, 7.5nm and 5nm.

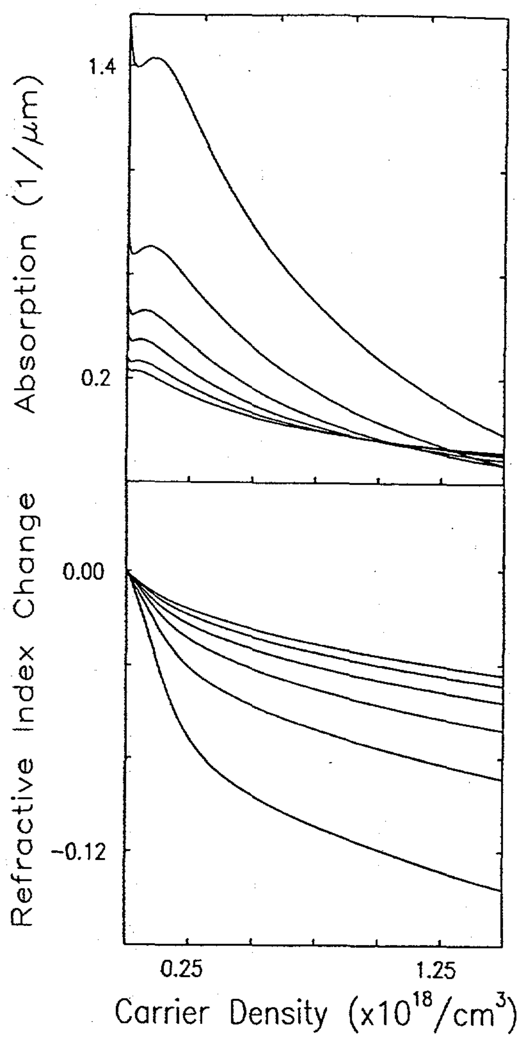

Figure 6. Absorption (top) and refractive index change (bottom) vs. carrier density at 1.06μm for a $In_xGa_{1-x}As$-GaAs quantum well. The curves are for the well width and Indium concentration combination, (a) 17.5, 0.263, (b) 15, 0.267, (c) 12.5, 0.274, (d) 10, 0.297, (e) 7.5, 0.306, and (f) 5, 0.353.

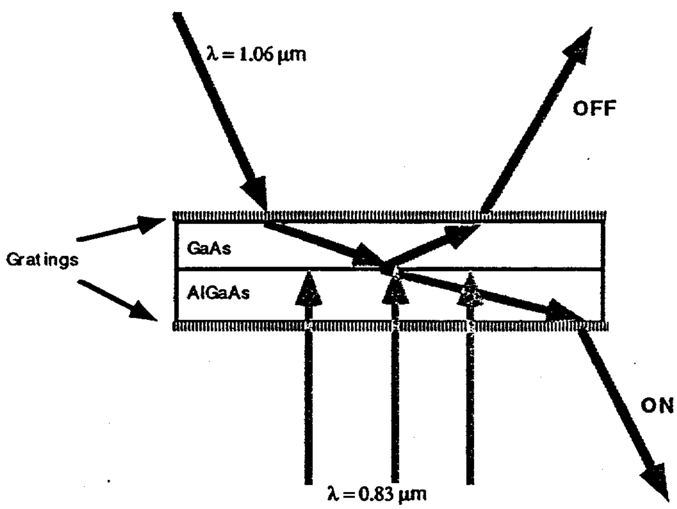

Figure 7. Grating coupled optical switch.

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