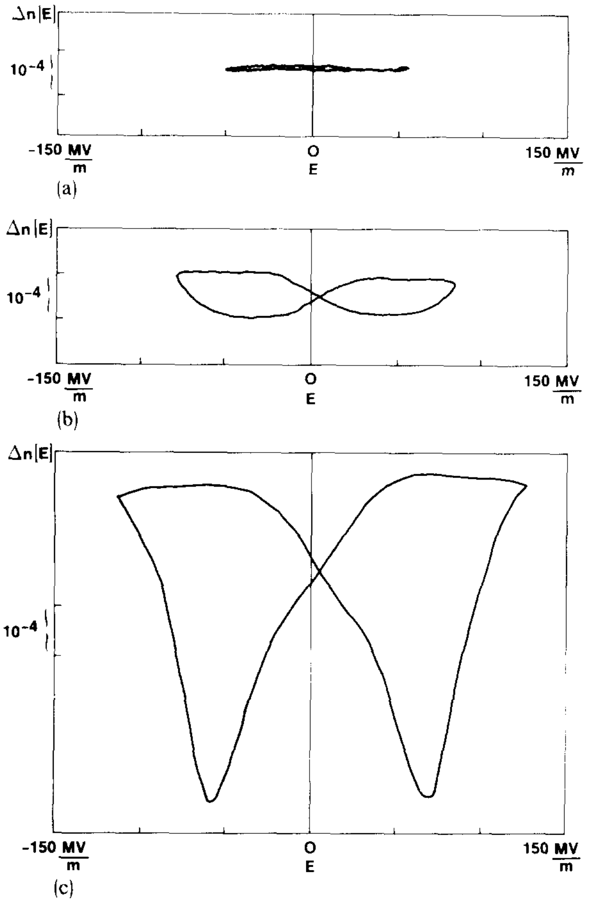

FIG. 2. Electrically induced birefringence vs electric field. Maximum fields: (a) 58 MV/m, (b) 83 MV/m, (c) 120 MV/m.

term leads to the prediction of a butterfuly hysteresis curve for $\Delta n[E]$ vs E.[14]

In the case of uniaxially drawn PVDF the polarization is not symmetric about the axis of incident light. However, it is reasonable to assume that the average angle between the draw direction and the direction of dipole orientation is $\pi/2$. Hence the longitudinal electro-optic effect gives the change in index of refraction as

$$\Delta n(\theta) = \Delta n_{\max}(\cos^2\theta - 1)\,. \tag{2}$$

Since this expression also shows a $\cos^2\theta$ dependence a butterfuly curve is expected for PVDF. The data in Fig. 2(c) show an unsaturated butterfly hysteresis curve in accordance with the theoretical prediction. The value of $\Delta n_{\max}$ for PVDF can be calculated from Fig. 2(c) and is approximately 7×10^{-4}.

Longitudinal electro-optic hysteresis in PVDF has been demonstrated and shown to be similar to electro-optic hysteresis predicted for transparent ceramics.

The authors wish to thank J. C. Hicks for helpful discussions and to acknowledge the technical assistance rendered by W. H. Morris. This work was supported by the Independent Research program at the Naval Ocean Systems Center.

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Direct polarization switching in semiconductor lasers

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(Received 11 May 1984; accepted for publication 3 July 1984)

Direct polarization switching controlled by the level of the injection current is achieved in InGaAsP lasers operating near the polarization transition temperature. The laser output can be switched from a pure TM_{00} mode at low injection currents to a TE_{00} mode at high currents with high extinction ratios and nanosecond response time. Conditions for polarization switching in InGaAsP and AlGaAs lasers at room temperature are also discussed.

Electronically controlled polarization modulators or switches are important components for high-speed optical communication and data transmission systems. At the present time, bulk and waveguide polarization switches based on the use of the electro-optic effect are the most commonly used passive devices. In this letter, we report direct polarization switching in semiconductor lasers. The devices are conventional InGaAsP/InP buried heterostructure lasers operating near the polarization transition temperature.[1] The polarization switching of the laser output is achieved by a relative change in the net gain of the TM (electric field normal to the junction) and TE (electric field parallel to the junction) modes through a small perturbation of the junction temperature induced by the injection current. The switching has high extinction ratio and can take place within one nanosecond when the laser is driven by fast-rising current pulses. To our knowledge, this is the first direct polarization switching in active devices ever reported. We also discuss device considerations for the fabrication of polarization-switchable lasers that operate at room temperature.

In a previous paper,[1] we reported a temperature-dependent polarization behavior of semiconductor lasers. Briefly, some well-behaved InGaAsP/InP lasers are found to operate in a pure TM_{00} mode or in a mixture of TE and TM modes at low temperatures although they normally operate in the TE_{00} mode at room temperature. For those which operate in a pure TM_{00} mode, the TE to TM transition occurs at a temperature T_c, characteristic of each individual laser. The polarization change is attributed to a thermal-stress effect in the InGaAsP active layer, which induces a relative change in the optical gain of the two modes.

When a laser is operated in the transition regime at a few degrees below T_c, the P-I curve, in general, has many kinks at different power levels caused by complex transverse mode competition among the fundamental and higher order TE and TM modes. In the simplest case, the P-I curve exhibits a kink at a transition current I_{c1}, shown in Fig. 1, which is associated with the TM_{00} to TE_{00} mode transition. A second kink is observed at a higher current I_{c3}, above which the laser starts to operate in a mixture of TE and TM modes because of spatial hole burning.[2] The laser output is purely TM polarized at low injection currents. If there is a window between I_{c2} and I_{c3}, the power can be switched to the TE mode when the amplitude of the current above I_{c1} is large enough to locally raise the junction temperature above T_c. The temperature change needed to induce the switching is of the order of 1 °C. This can be achieved by controlling the level of the injection current. To demonstrate this switching behavior, we select a InGaAsP/InP buried heterostructure laser which has a large window between I_{c2} and I_{c3}. The transition temperature of this laser is -68 °C. The polarization-resolved power-current characteristics, shown in Fig. 1, are taken at -71 °C. The pulse waveforms of the laser driven by two successive 30-ns current pulses with amplitudes above and below the transition current, I_{c1}, are shown in Fig. 2. In Fig. 2(a) where the smaller current pulse leads the larger one, the output of the laser switches from a TM-polarized pulse to a TE-polarized one. When the larger current pulse takes the lead, the laser switches from TE to TM, as shown in Fig. 2(b).

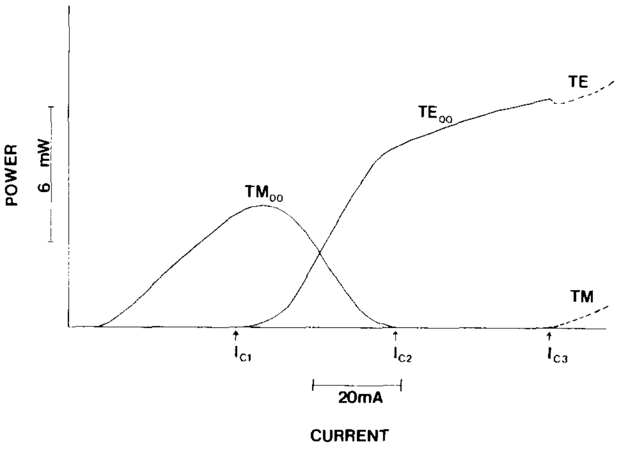

FIG. 1. Pulsed polarization-resolved power vs current characteristics of a InGaAsP laser measured at -71 °C. The critical temperature for the polarization transition in this laser is -68 °C. The pulse width is 30 ns.

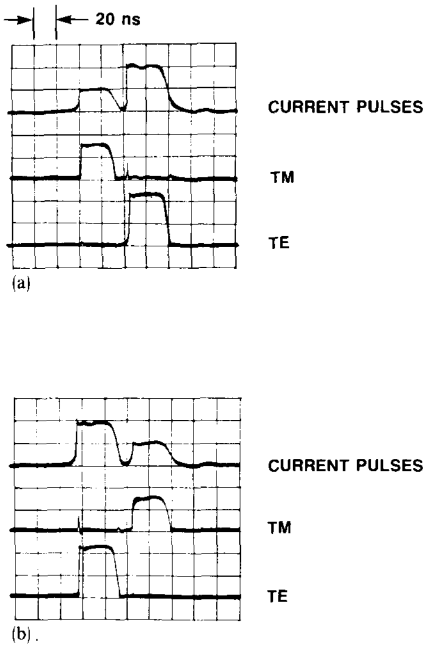

FIG. 2. Waveforms of current pulses (top traces) and laser pulses in the TM polarization (middle traces) and in the TE polarization (lower traces). In (a), the smaller current pulse leads the larger current pulse. The order is reversed in (b).

The extinction ratio of the switching, defined as the ratio of the energy of the pulse in the operating polarization to that of the remnant in the orthogonal polarization, is very high. For currents below I_{c1}, the stimulated emission is purely TM polarized. The extinction ratio is only limited by the amount of spontaneous emission in the TE polarization. In the case of Fig. 2 where the amplitude of the smaller current pulses is close to $I_{c1} = 40$ mA, the extinction ratio is 60. For currents above I_{c1}, the TE emission switches on immediately following a small transient TM emission in the leading edge of the pulse. When the laser is driven by a long current pulse with amplitude slightly above I_{c1}, the transition from TM to TE can take several hundred nanoseconds.[1] In the switching operation with fast-rising current pulses of sufficiently high amplitude above $I_{c2} \simeq 80$ mA, detector-limited transient TM spikes as short as 200 ps are observed. The current pulses in Fig. 2 have a rise time of 2 ns. The duration of the corresponding transient TM spikes is less than 2 ns. This transient spike is determined by the rise time and the amplitude of the current pulse and is not affected by the change in the duration of the pulse. For the 30-ns pulses in Fig. 2, the total energy in the TM spike is about 1/70 of that in the TE pulse. When the TM spontaneous emission is included, the overall extinction ratio for the TE operation is about 40. The extinction ratio for the TE operation increases with increasing pulse duration for nanosecond pulses. In principle, the transient TM emission can be further shortened by increasing the amplitude of the driving current pulse. In actuality, the maximum extinction ratio for the TE mode is limited by a spatial hole-burning effect which causes the laser to operate in a mixture of TE and TM modes in the presence of a very strong TE mode. In this example, the hole burning occurs at a very high power level corresponding to $I_{c3} = 120$ mA. In some lasers, however, spatial hole burning occurs prematurely at currents less than I_{c2} or I_{c1}, resulting in low extinction ratios for the TE operation. The spatial hole-burning effect can be suppressed by reducing the width of the active layer.[3]

We find that the polarization switching can be operated quite successfully with various combinations of nanosecond pulses of different durations and amplitudes, separated as close to 2 ns. The pulse shape and polarization of the second laser pulse are solely controlled by the level of the second current pulse and are not influenced by the presence of the first pulse. This indicates that cooling of the junction after a current pulse is a fast process. This is not surprising because cooling of an active layer of $2l \simeq 0.2$-μm thickness has a subnanosecond time constant. The heat diffusion constants D for InGaAsP and InP are not available to us. If we take $D = 0.28$ cm^2/s at $T = 300$ K (D increases with decreasing temperature) for GaAs,[4] the time constant for a two-sided diffusion process from a 0.2-μm layer is estimated to be $t = l^2/2D \simeq 180$ ps for $l = 0.1\,\mu$m. The subnanosecond cooling rate is important for reducing bit pattern effects. When the laser is continuously driven by a train of current pulses, the fast cooling rate should also allow fast polarization switching of the laser except that the operating temperature needs to be appropriately lowered to compensate for the average junction heating.

The polarization switching experiment described in this paper was carried out at -71 °C. For practical applications, it is desirable to operate the devices at room temperature. This can be achieved by introducing a sufficient internal strain in the active layer so that the polarization transition occurs at room temperature. For InGaAsP/InP lasers, the strain can be easily created by introducing a small amount (of the order of 10^{-4}) of lattice mismatch between the InGaAsP active layer and the InP cladding layers and InP substrate.[1] For AlGaAs/GaAs lasers made of conventional double heterostructure materials, thermal stress cannot cause enough strain to induce the TM mode at room temperature because the stress in the active layer caused by the cladding layers is largely offset by the GaAs substrate.[1] This stress, however, can be enhanced by growing a thick buffer layer with appropriate aluminum concentration[5] and by thinning the GaAs substrate.[2] The actual thickness and compositions of the buffer layer depend on those of the active layer and the cladding layer. Detailed device considerations will be published elsewhere.

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Channeled-substrate GaAs/AlGaAs multiple quantum well lasers grown by molecular beam epitaxy

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(Received 29 May 1984; accepted for publication 3 July 1984)

(GaAl)As/GaAs multiple quantum well channeled-substrate lasers with lateral index guiding have been made by molecular beam epitaxy. They operate stably in a single longitudinal mode.

Single and multiple quantum well (MQW) lasers have been extensively investigated.[1,2] Besides their low threshold current density, these quantum well heterostructure lasers exhibit good linearity in light-output versus current characteristics, a high external differential quantum efficiency, and a high value of T_0 which is a measure of lesser temperature sensitivity in the laser threshold current. To date, however, there have been few studies[3,4] concerning the incorporation of index guiding in the quantum well lasers which is of great interest for practical applications. For fiber-optical commu-