CaF_2 crystals we had grown in order to measure the displacement of the OH^- absorption band from the UV cut-off wavelength. Hydroxide-associated absorption is a maximum in these fluorides at about 2.0–2.2 eV less than the UV cut-off energy.

The published[11] cut-off wavelength of LaF_3 is 125 nm (9.9 eV). Our measurements of undoped LaF_3 indicate that the cut-off wavelength is closer to 120 nm (10.3 eV). From these data and the mean displacement energy of OH^- in fluorides (2.1 eV), we calculate that the OH^- absorption peak should lie between 151 and 159 nm. Symmetry of the absorption curves of Fig. 3 about 159 nm—midway between excitation and fluorescence wavelengths—would produce some diminution of output from the 0.1% crystal. However, absorption in the 0.5% and 1.0% crystals would be far greater. Laser action might be sustained in the lightest doped crystal, but would be unlikely in the others. If the impurity-absorption line is closer to 151 nm, a greater fraction of the exciting light would be absorbed, and the concentration effect would be exaggerated. All these observations are consistent with hydroxide contamination of the dopant.

Increased output from Nd^{3+}:LaF_3 laser can be expected from purer crystals. A coaxial system, in which the exciting gas fills the space between the crystal and a thin cylindrical electrode, would also promote efficiency. Such a system is nearly complete. These improvements should make possible tunable laser output over the 170–175-nm region.

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Polarization bistability in semiconductor lasers

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A new kind of optical bistability, the polarization bistability, is observed in InGaAsP/InP lasers operating near the polarization transition temperature. This bistability is characterized by large hysteresis loops in the polarization-resolved power versus current characteristics. Fast switching between the two stable polarization states by injection of current pulses is also demonstrated.

There has been considerable interest in bistable optical devices which are able to perform optically controlled memory and switching operation in all-optical systems. The simplest method of achieving optical bistability in passive devices involves a saturable absorber or a nonlinear refractive medium placed in an optical cavity.[1] On the other hand, bistable operation in light-emitting devices has been demonstrated using inhomogeneous current pumping,[2,3] optical injection,[4] and coupled laser cavities.[5]

In this letter, we report a new kind of optical bistability, polarization bistability, in semiconductor lasers. The phenomemon is observed in some InGaAsP/InP lasers operating near the polarization transition temperature,[6] which is characteristic of each individual laser. In this temperature regime, the lasers operate in a pure TM_{00} mode at low injection currents and switch operation to a pure TE_{00} mode at high injection currents. Large hysteresis loops with high contrast ratios are observed in the polarization-resolved power versus current characteristics, while the total power exhibits only slight changes in the hysteresis. The switching behavior of the TE mode is therefore complementary to that of the TM mode. Switching between the two stable polarization states by injection of short current pulses is also demonstrated.

The lasers are V-grooved substrate buried heterostructure InGaAsP/InP lasers emitting at 1.3-μm wavelength.[7] Approximately 15% of the lasers tested exhibit the polarization bistability. The polarization-resolved cw power-current characteristics of a laser at various temperatures of interest are shown in Fig. 1. At 195.2 K and above, this laser operated in a pure TE mode and the power-current characteristics are kink-free. The threshold current is 3.5 mA at 195.2 K. Below this temperature, the laser output starts to show the

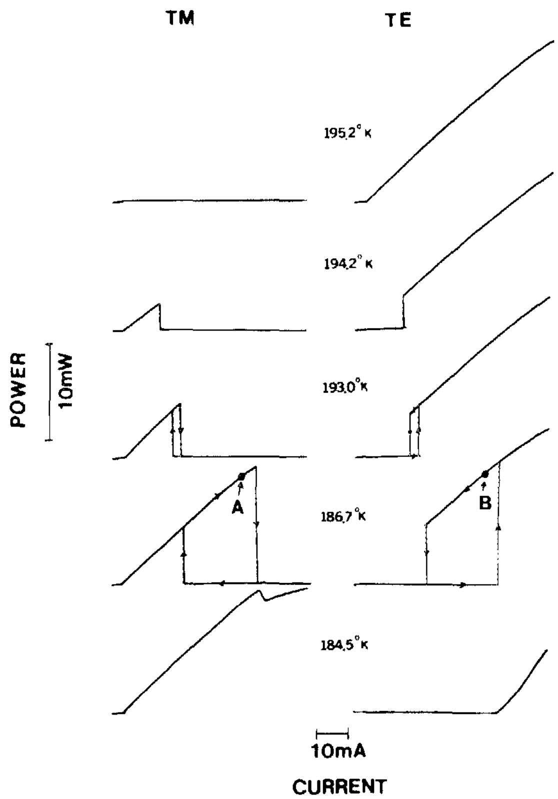

FIG. 1. Polarization-resolved power vs current characteristics of a polarization-bistable laser at various temperatures. Notice that the injection current is negative.

TM stimulated emission above the threshold current. The temperature-dependent polarization behavior is attributed to the internal thermal stress in the active layer which modifies the band structure and thereby changes the optical gain of the TM mode relative to that of the TE mode.[6] The TM stimulated emission quickly becomes dominant with decreasing temperature. At 194.2 K, the laser operates in a pure TM mode at low injection currents and abruptly switches operation to a pure TE mode at 15 mA. From a thermal impedance measurement, the junction temperature increase at 15 mA is estimated to be 0.8 °C, sufficient to move the laser into the TE-dominated regime. With further decreases in the temperature, hysteresis loops can be observed in the polarization-resolved power-current characteristics. The width of hysteresis loop varies from $\simeq 1$ mA at 193.5 K to 23 mA at 186.7 K. Below 186.7 K, the laser operates in a pure TM mode at low injection currents and switches into a mixture of TE and TM modes at 45 mA and the hysteresis disappears.

The far-field patterns parallel to the junction plane and the lasing spectra of the TM and TE modes in the bistable regime are shown in Fig. 2. The data are taken at the same temperature with the same injection current, labeled by points A and B in Fig. 1. The far-field patterns of TM and TE modes are both single-lobed and centered within one degree from each other. The beam divergence is 23.4° for the TM mode and 24.5° for the TE mode. The lasing spectra of the TM and TE modes both consist of a family of equally spaced longitudinal modes separated by 10.8 Å. The TE family lies

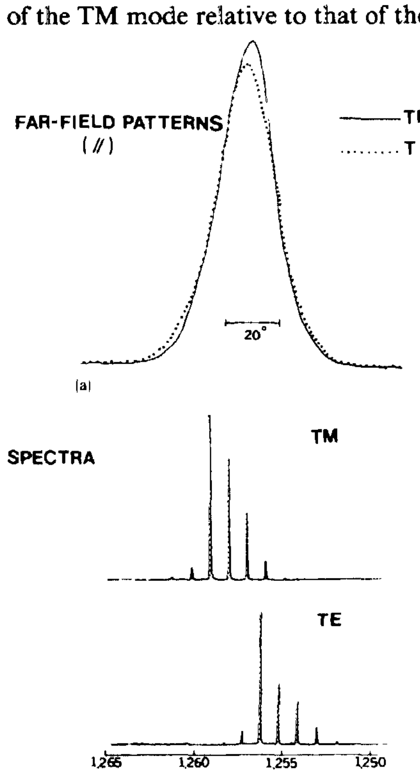

FIG. 2. Far-field patterns (parallel to the junction) and lasing spectra of the TM and TE modes measured under the conditions of A and B, respectively, in Fig. 1.

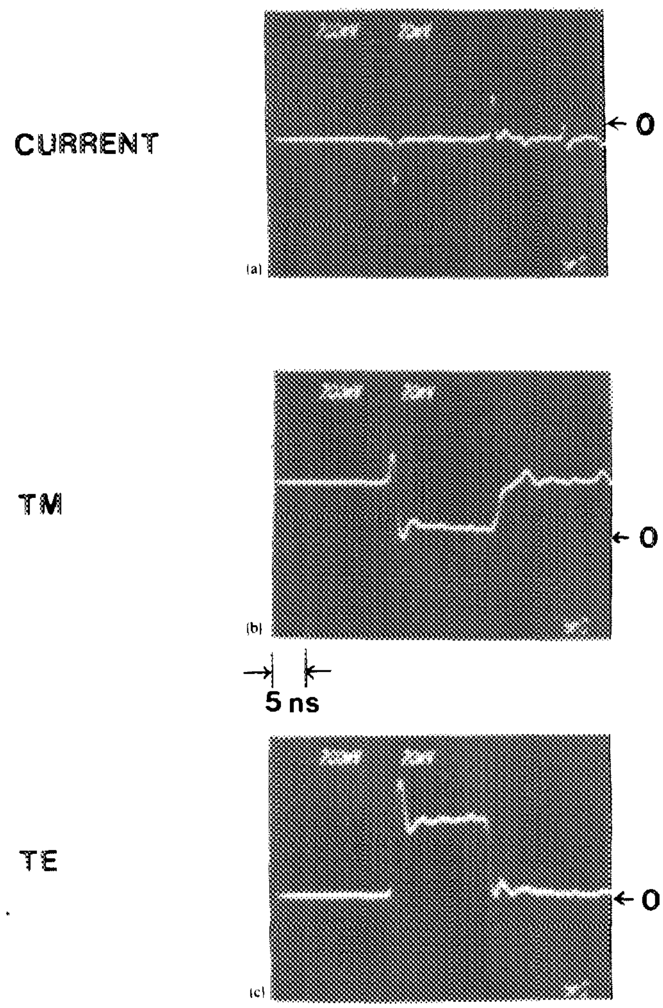

FIG. 3. High speed switching between the polarization bistable states by injection of current pulses. (a) Switching current pulses on a -20 mA dc bias current. (b) TM optical output. (c) TE optical output.

on the shorter wavelength side of the TM family, shifted by 30 Å. From the smooth and single-lobed far-field patterns and the well-behaved longitudinal mode spectra, it is clear that the two orthogonally polarized modes occupy nearly the same space and can be designated as the TM_{00} and TE_{00} modes. This is very important for practical applications because the two polarization states can be simultaneously coupled into a fiber or a waveguide without relative beam movement.

When the laser is biased within a hysteresis loop, it can be switched between the two stable states of different polarization by injection of short electrical or optical pulses. To demonstrate the switching operation, the laser is operated in the middle of the hysteresis loop at 193.0 K with a dc bias current of -20 mA. The width of the hysteresis loop is 3.5 mA at this temperature. This small hysteresis loop is chosen to minimize the pulse amplitude needed to overcome the phenomenon of critical slowing down.[8] The switching behavior by injection of current pulses is presented in Fig. 3. The laser initially operates in the TM mode. A negative current pulse switches the laser output to the TE mode while a subsequent positive current pulse switches the laser output back to the TM mode. With a pulse amplitude of 40 mA, the switching takes place within 2 ns, limited by the rise time of the current pulses and the time resolution of the oscilloscope.

The hysteresis described above reflects the existence of a self-induced stabilization mechanism for the existing lasing mode to resist the onset of a new lasing mode as the peak of the gain profile is shifted. Such a mechanism, for example, could originate from modualation of the inverted population by the intense stimulated emission,[9–12] which is known to cause hysteresis in wavelength versus temperature and wavelength versus current characteristics in semiconductor lasers.[10,11] In fact, the observed longitudinal mode hopping of 30 Å ($\Delta h\nu = 2.4$ meV) accompanying the polarization switching is comparable to the width of the gain modulation inferred from the longitudinal mode behavior of InGaAsP/InP lasers[12] and directly observed in AlGaAs/GaAs lasers.[10] The exact cause of the polarization bistability is still being investigated.

In conclusion, we have observed polarization bistability in InGaAsP/InP lasers. The bistability is characterized by large hysteresis loops in the polarization-resolved power versus current curves. In the bistable regime, the transverse modes of the two stable states are identified as the TM_{00} and TE_{00} modes. Switching between the two stable states by injection of short current pulses is also demonstrated.

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