Longitudinal-mode partitioning, that will result in error counts in a high-bit-rate long-haul optical fiber system,[8] is suppressed in GRECC lasers even under high-speed modulation. Figure 4(a) shows the spectrum of one of the 1.55-μm GRECC lasers with 2-Gbit/s nonreturn-to-zero (NRZ) pseudorandom pulse modulation. A 1700:1 side mode suppression ratio is shown in the 100× expanded scale. A spectrometer was used as a mode filter to pass only the dominant mode. The detected pulse stream was checked for errors using a bit-error-rate receiver, and an error rate of less than 10^{-11} was obtained. Figure 4(b) shows both a clean eye pattern after the spectrometer and a 10:1 on/off power extinction ratio. Similar error-free performance was obtained for a 1.3-μm GRECC laser modulated at 1 Gbit/s. These results confirm the dynamic single-longitudinal-mode operation of GRECC lasers.

Digital lightwave transmission at 1 Gbit/s over 99.06 km of single-mode fiber was demonstrated with a GRECC laser at 1.55-μm wavelength. Figure 5 shows the block diagram of the laboratory transmission system; it is similar to an earlier transmission experiment which used a mode-stabilized cleaved-coupled-cavity laser.[9] The GRECC laser was operated by a laboratory high-speed transmitter and the laser stud temperature was held at 28 °C with a thermoelectric cooler. The fiber had a dispersion minimum at 1.3 μm and a dispersion of 17 ps/km nm at 1.55 μm. The total fiber loss including eight splices and two biconic connector pairs was 24.4 dB at 1.55 μm. A back-illuminated InGaAs *pin* photodiode[10] was used in the receiver. The average power launched into the fiber was 0.96 dBm and the on/off power extinction ratio was 3.5:1. The bit-error-rate curve in Fig. 6 was generated by decoupling the fiber output to the receiver. The nearly straight curve indicates negligible penalty due to mode partitioning. Despite a power penalty of approximately 3 dB caused by the low-power extinction of 3.5:1, an error rate of 1×10^{-9} was obtained with a received light power of -26.5 dBm.

In summary, we have demonstrated a single-longitudinal-mode GRECC laser which is attractive for its simplicity. The external cavity, prepared from multimode optical fiber, can be applied in a straightforward way to conventional semiconductor lasers. Its application in high-bit-rate long-haul systems has been demonstrated by a 1.55-μm, 1-Gbit/s transmission experiment over 99 km of single-mode fiber.

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Temperature-dependent polarization behavior of semiconductor lasers

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InGaAsP lasers are found to operate in a pure TM mode or in a mixture of TE and TM modes at low temperatures. The polarization change at low temperatures is attributed to a thermal-stress effect in the InGaAsP active layer. However, none of the AlGaAs/GaAs lasers tested exhibits such behavior because the thermal stress in the active layer is significantly offset by the GaAs substrate.

Semiconductor lasers normally operate in the TE mode (electric field parallel to the junction) because of the higher mirror reflectivity of the TE mode compared to that of the TM mode (electric field normal to the junction). It has been shown that the TM mode can be induced by applying a uniaxial compressive stress normal to the junction on the active layer.[1-3] This lifts the degeneracy of the valence bands and thereby changes the relative contribution of the light and heavy hole interband transitions.[2]

In this letter, we report a temperature-dependent polarization behavior in semiconductor lasers. We find that some well-behaved, TE-polarized InGaAsP/InP lasers operate in a pure TM mode or in a mixture of TE and TM modes at low temperatures. The onset of the TM mode occurs at a critical temperature ranging from room temperature to the lowest temperature (77 K) achievable in our apparatus, characteristic of each individual laser, and is accompanied by a kink in the power-current relationship. The phenomenon is observed in InGaAsP/InP lasers of different structures, but in none of the AlGaAs/GaAs lasers. We attribute the polarization change to a thermally induced stress effect resulting from the difference in the thermal expansion coefficients of the InGaAsP active layer and the InP cladding layers and InP substrate. The observed transition temperatures are in agreement with those estimated from a stress analysis. However, the thermal stress in the AlGaAs/GaAs lasers is 20 times smaller because the stress induced by the thin cladding layers is largely offset by the thick GaAs substrate whose composition is similar to that of the active layer. This explains the absense of mode switching in AlGaAs/GaAs lasers.

The InGaAsP/InP lasers studied are buried heterostructure lasers and stripe-geometry lasers operating at 1.3-μm wavelength, from internal and commercial sources. The active layers of the buried heterostructure lasers are planar or crescent shaped. The laser chips are bonded on copper, silicon, or diamond heat sinks with p side down. All lasers operated in a TE mode at room temperature.

Figure 1(a) shows the pulsed power-current (P-I) characteristics of a buried crescent at various temperatures. At room temperature and above the laser operates in a pure TE mode. When the temperature is lowered to a critical temperature, which is -40 °C for this laser, the laser output starts to show a mixture of TE and TM modes. The TM mode gradually becomes dominant with decreasing temperature and the laser operates exclusively in the TM mode at temperatures lower than the critical temperature by 10 °C or more. However, some lasers remain in a mixture of TE and TM modes to the lowest temperature (77 K) achievable with our experimental appartus. When the laser operates in a pure TE or TM mode, the P-I curves are kink-free. In the transition regime near the critical temperature, kinks are observed at current levels where the laser switches from the TM mode at low injection currents to the TE mode at higher currents. The detailed behavior of the mode transition process is illustrated by the polarization-resolved P-I curves in Fig. 1(b). When the laser is driven by a long current pulse, the TM mode is observed in the leading edge of the laser pulse and the transition to the TE mode takes place after $\simeq 1$-μs delay. The time delay decreases with increasing current and with increasing temperature. This indicates that the TM to TE switching is induced by current-induced heating of the junction.

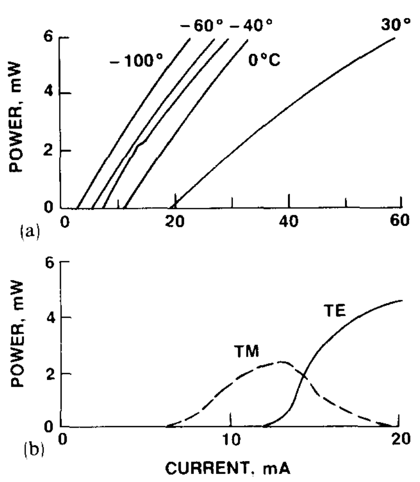

FIG. 1. (a) Pulsed P-I curves of an InGaAsP/InP laser at various temperatures. The pulse width is 100 ns. (b) Polarization-resolved pulsed P-I curves measured at -40 °C.

The onset of the TM stimulated emission occurs at a temperature ranging from room temperature to 77 K. However, none of the AlGaAs/GaAs lasers studied, including the channeled substrate planar structure, the oxide-defined narrow-stripe structure, and the proton-bombarded single quantum well structure, operates in the TM mode even at the lowest temperature.

We attribute the polarization change of the InGaAsP/InP lasers at low temperatures to a relative change in the optical gain of the two modes, caused by a thermally induced internal stress in the active layer. The thermal expansion coefficient of the InGaAsP active layer is larger than that of the InP substrate.[4,5] As the temperature decreases, the active layer experiences a tensile stress along the junction plane. As a result, the lattice constant parallel to the junction plane becomes larger than that normal to the junction.[6] The deformed lattice structure is equivalent to that created when a uniaxial compressive stress is applied normal to the junction. This can lead to an increase in the probability of the TM emission.[2,3,7]

A stress analysis is carried out for a typical $In_{1-x}Ga_xAs_yP_{1-y}$/InP double heterostructure shown in Fig. 2(a). Assuming that the substrate is much thicker than the epitaxial layers, the stress in the active layer caused by a temperature change ΔT can be expressed by[8–10]

$$\sigma_{xx} \simeq -\frac{E}{1-\nu}\frac{(t_s + 2t_c - 3t_a)}{t}\Delta\alpha_i \Delta T, \qquad (1)$$

where E is the Young's modules, ν is the Poisson's ratio, and $\Delta\alpha_i = \alpha_{\mathrm{InGaAsP}} - \alpha_{\mathrm{InP}}$ is the difference of the thermal expansion coefficients of InGaAsP and InP. As an example, we consider a laser with a (100) substrate operating at $\lambda = 1.3$ μm, which corresponds to $y = 0.64$.[5] For this case, we have[5] $E = 6.5\times 10^{11}$ dyn/cm^2, $\nu = 0.341$, $\alpha_{\mathrm{InGaAsP}} = 5.37\times 10^{-6}$/°C, $\alpha_{\mathrm{InP}} = 4.56\times 10^{-6}$/°C, and $\sigma_{xx} = -8\times 10^5 \Delta T$ dyn/cm^2 °C, which is tensile when $\Delta T < 0$. For the layer dimensions specified in Fig. 2, the strain normal to the junction is given by $\varepsilon_{zz} = -(2\nu/E)\ \sigma_{xx} = 8.4\times 10^{-7} \Delta T$/°C.

The lattice deformation in the active layer caused by this strain per degree decrease of temperature is equivalent to the effect of an external uniaxial compressive stress of 0.82 atm normal to the junction. According to Dutta's calculation,[7] the relative increase in the optical gain of the TM mode over the TE mode induced by a uniaxial compressive stress is 0.14 cm^{-1}/atm. Based on this analysis, cooling of the laser should induce a relative increase in the TM optical gain of

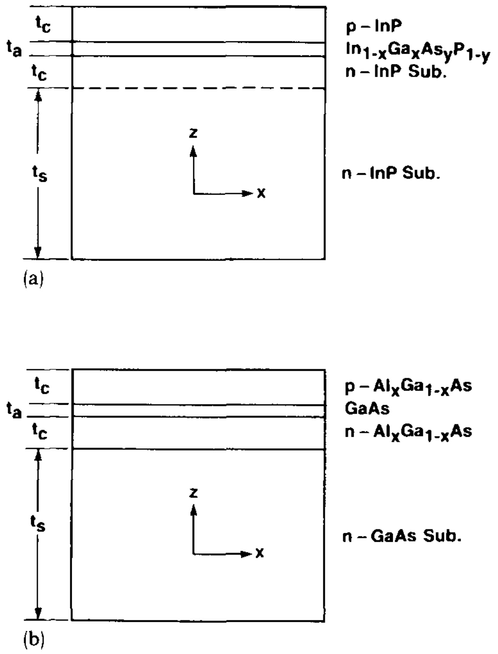

FIG. 2. (a) Simplified layer configuration of an InGaAsP/InP DH structure with typical dimensions: $t_s = 75$ μm, $t_c = 1$ μm, $t_a = 0.2$ μm and $t = t_s + 2t_c + t_a$. The z axis is parallel to the [100] direction. (b) Simplified layer configuration of an AlGaAs/GaAs DH structure. The dimensions are the same as (a).

$0.115\ \text{cm}^{-1}/^\circ\text{C}$. In these lasers, the net gain of the TM mode, including the mirror losses, is typically smaller than that of the TE mode by 5–10 cm^{-1} at room temperature,[11] as determined by the contrast ratio of the Fabry–Perot mode spectra.[12] A temperature change of -40 to -100 °C from the room temperature will offset this gain difference, resulting in TM mode operation of the InGaAsP laser. This is in good agreement with our observation.

A similar calculation for a typical $Al_x Ga_{1-x}As$/GaAs DH structure in Fig. 2(b) yields

$$\sigma_{xx} \simeq -4\frac{E}{1-\nu}\frac{(2t_c)}{t}\Delta\alpha_g \Delta T, \tag{2}$$

where $\Delta\alpha_g = \alpha_{\text{AlGaAs}} - \alpha_{\text{GaAS}}$ is the difference of the thermal expansion coefficients of AlGaAs and GaAs. Equation (2) has a different form from that of Eq. (1) because the relationship between the active layer and the substrate is completely different. For the GaAs active layer, $E = 8.53\times 10^{11}$ dyn/cm^2,[5] $\nu = 0.312$,[5] and $\alpha_{\text{GaAs}} = 6.78\times 10^{-6}/^\circ\text{C}$.[13,14] If we consider the cladding layers with $x = 0.3$, then $\alpha_{\text{AlGaAs}} = 6.31\times 10^{-6}/^\circ\text{C}$, and the stress in the active layer $\sigma_{xx} = -6\times 10^4\ \Delta T$ dyn/cm^2 °C, which is also tensile when $\Delta T < 0$. The corresponding strain is given by $\varepsilon_{zz} = 4.4\times 10^{-8}\ \Delta T/^\circ\text{C}$ which is 20 times smaller than that calculated for the InGaAsP/InP structure. Notice that this gives the upper limit of ε_{zz} in the AlGaAs/GaAs lasers because the aluminum concentration of a few percent in the active layer of most lasers will futher reduce the thermal stress σ_{xx}. This explains the absence of the polarization change in AlGaAs/GaAs lasers at low temperatures. The most significant factor that makes the AlGaAs/GaAs structure different from the InGaAsP/InP structure is that the stress in the active layer caused by the AlGaAs cladding layers is largely offset by the thick GaAs substrate whose composition is close to that of the active layer. Experimentally, it has been shown that [1,2] an external uniaxial compressive stress of the order of 100 atm is needed to induce enough lattice deformation for the TM mode operation in AlGaAs/GaAs lasers at room temperature. Our analysis shows that such deformation can never be achieved solely by cooling, unless a very thick AlGaAs cladding layer is incorporated.[15]

In conclusion, we have shown that the TE mode to TM mode transition in InGaAsP/InP lasers at low temperatures can be explained by a thermally induced stress effect in the active layer. However, the AlGaAs/GaAs lasers do not exhibit such behavior because the thermal stress in the active layer is largely offset by the GaAs substrate. To avoid the TM emission, it is important to control the crystal growth condition so that the epitaxial layers are perfectly lattice matched at the device operating temperature.

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