Single longitudinal mode operation of long, integrated passive cavity InGaAsP lasers

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We propose a new 1.3-μm wavelength InGaAsP laser—the integrated passive cavity (IPC) laser—and demonstrate its device performances compared with conventional lasers fabricated under similar procedures. The long IPC laser (3.55-mm-long passive cavity), as well as the short IPC laser, exhibited single frequency oscillation even just above the threshold, and the maximum ratio of longitudinal main to submode exceeded 30 dB. They also showed favorable effects in the oscillation frequency stabilization.

For future high-quality optical fiber communication systems, it is essential to have stable single frequency semiconductor lasers as optical sources. Over the past few years, a number of device geometries have been proposed to fabricate such lasers. They include distributed feedback (DFB) lasers,[1] distributed Bragg reflector (DBR) lasers,[2] cleaved-coupled-cavity (C^3) lasers,[3] short coupled-cavity (SCC) lasers,[4] and graded index rod (GRINROD) external coupled-cavity lasers.[5] Although they can be operated in a single longitudinal mode, narrowing of the spectral linewidth and reduction of the frequency chirping under amplitude modulation are required to utilize them for coherent communication systems, long-haul transmission systems, and analog video transmission systems.[6] On the other hand, long external cavity lasers have been proposed for oscillation frequency stabilization.[7-10] They have a short semiconductor gain medium with a long external cavity, where longer cavity is shown to be effective for the stabilization. The results of the frequency stabilization, such as narrowing of the spectral linewidth[7,8] and reduction of the frequency chirping,[8,9] have been demonstrated in the external cavity laser constructed with a mirror or a diffraction grating. To realize a mechanically stable device, however, integrated configuration, i.e., monolithic integration of the long passive cavity with the active cavity, is desirable. As for the integration, the active/passive cavity GaAs lasers have already been reported,[11,12] but they have rather short passive cavities which are not suitable to achieve frequency stabilization.

We propose a new device geometry that enables one to integrate a long passive cavity with an InGaAsP laser and demonstrate the operation characteristics of this integrated passive cavity (IPC) laser. The passive cavity is a loaded waveguide that is self-aligned to the active cavity. This self-aligned integrated loaded (SAIL) guide was fabricated easily with a selective etching method. The long IPC laser, as well as the short IPC laser, exhibited a single frequency oscillation even just above the threshold, and it also showed the effects of the frequency stabilization.

The structure of the SAIL guide IPC laser is shown in Fig. 1. To fabricate SAIL guide lasers, six layers were first grown on (100) oriented n^+-InP substrates, which were an n-InP buffer layer, an n-InGaAsP waveguide layer (band-gap wavelength $\lambda_g = 1.05\ \mu$m, 0.5 μm thick), an n-InP separation layer (0.15 μm thick), an undoped InGaAsP active layer ($\lambda_g = 1.3\ \mu$m, 0.13 μm thick), a p-InP clad layer, and a p-InGaAsP cap layer. Then stripe mesa etching and regrowth of p-InP and n-InP were done. In mesa etching, the wafer was etched down to the surface of the waveguide layer using a SiO_2 stripe mask. The cap layer was etched by Br-CH_3OH. The clad layer, the active layer, and the separation layer were etched by selective etchants: HCl:H_3PO_4 (1:2 in volume) for InP and H_2SO_4:H_2O_2:H_2O (1:1:5 in volume) for InGaAsP, to expose the surface of the waveguide layer. The stripe width of the active layer was $\sim 2.0\ \mu$m.

After the second growth, a part of the wafer, which would be the active cavity, was masked by SiO_2. The unmasked region was etched by CCl_4 reactive ion etching (RIE) to remove the cap layer and was then etched by the selective etchant for InP. As a result, the waveguide layer was exposed, except for the stripe region where the active stripe was left. The active layer was easily etched off by H_2SO_4 solution, and then the separation layer was left in the stripe shape (denoted by the load in Fig. 1), which was self-aligned to the active stripe. The passive cavity was made of this load and the waveguide layer. In this SAIL guide structure, the optical loss in the passive cavity is expected to be low because the light is confined transversely under the load. The scanning electron microscope (SEM) photograph of the SAIL guide is shown in Fig. 2. After removing the SiO_2 mask, the Au-Zn contact was formed on the active cavity and the Au-Sn contact on the substrate side.

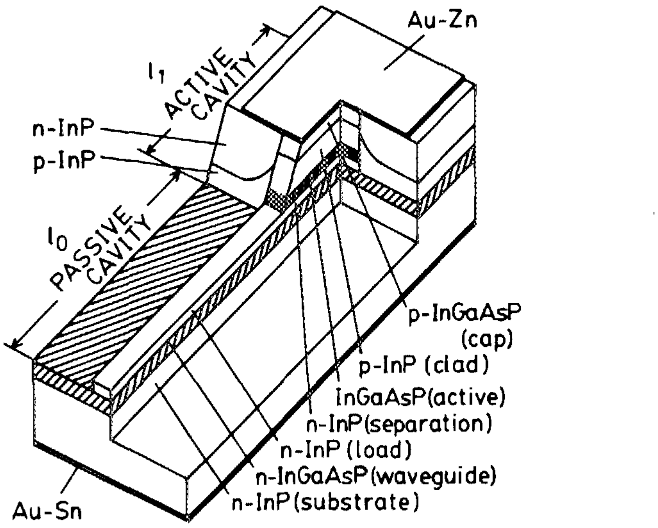

FIG. 1. Schematic drawing of the integrated passive cavity (IPC) laser with the self-aligned integrated loaded (SAIL) guide for the passive cavity.

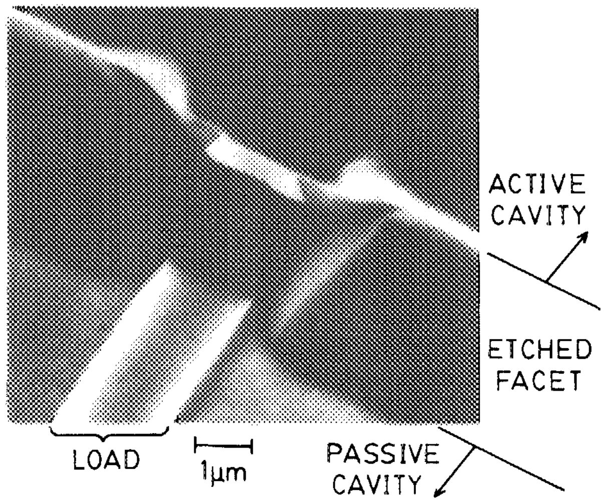

FIG. 2. SEM photograph of the etched facet between the active cavity and the passive cavity in the IPC laser.

The current-light output characteristics of three lasers at room-temperature pulse operation are shown in Fig. 3, where (a) is a long IPC laser, (b) a short IPC laser, and (c) a conventional laser. The passive/active cavity length ratios (denoted by l_0/l_1) of the long and the short IPC lasers were $3553\,\mu\mathrm{m}/400\,\mu\mathrm{m}$ ($\simeq 8.88$) and $273\,\mu\mathrm{m}/224\,\mu\mathrm{m}$ ($\simeq 1.22$), and the conventional laser had a 248-μm-long cavity, which was the same geometry as the active cavity of the IPC lasers. As seen in Fig. 3, the long IPC laser had a lower threshold current of 58 mA than the short IPC laser, whose threshold was 72 mA, though the conventional laser had the lowest threshold of 31 mA. Therefore, it is considered that the main reason for the threshold increasing is not due to the waveguiding loss in the passive cavity but to an optical coupling loss between the active cavity and the passive cavity.

The IPC lasers exhibited stable single frequency oscillations just above the threshold. The longitudinal mode characteristics of the long IPC laser, measured at 20 °C, cw operation for several driving currents, are shown in Fig. 4. From the viewpoint of the mode selectivity in a coupled cavity laser, $l_0/l_1 < 1$ is considered to be favorable for stable single longitudinal mode operation.[5] The long IPC laser ($l_0/l_1 \simeq 8.9$), however, showed a clean single frequency oscillation, and the maximum ratio of longitudinal main to submode exceeded 30 dB, whereas the laser without passive cavity showed the multimode oscillation.

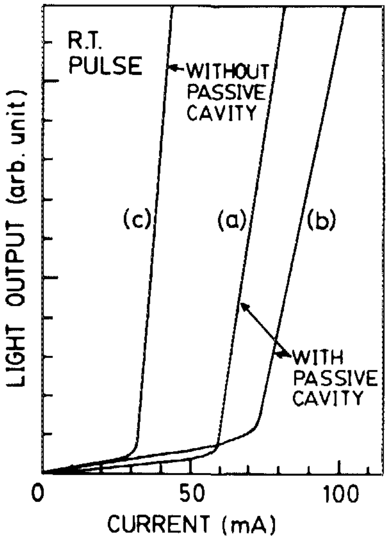

FIG. 3. Current-light output characteristics of (a) the long IPC laser ($l_0/l_1 = 3553\,\mu\mathrm{m}/400\,\mu\mathrm{m}$), (b) the short IPC laser ($273\,\mu\mathrm{m}/224\,\mu\mathrm{m}$), and (c) the laser without passive cavity (248 μm long).

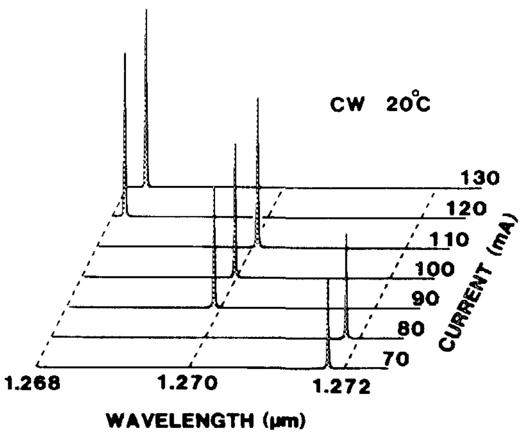

FIG. 4. Longitudinal mode characteristics of the long IPC laser for several driving currents.

By increasing the driving current, the oscillation mode was transferred to a shorter wavelength mode with a mode spacing of about 18 Å. This mode transfer is due to the mode selectivity of the coupled cavity and is well explained by the phase and gain conditions as follows. Device parameters of a model of the IPC lasers are denoted in Fig. 5(a), where r_0, r_1, and r_2 are the amplitude reflectivities of each boundary, and n_0 and n_1 are the refractive indices of the passive and the active cavities, respectively. The phase condition of this laser is written in the form[9,10,13]

$$\tan\phi_1 = f(\phi_0), \tag{1}$$

with

$$f(\phi_0) = r_0(r_1^2 - 1)\sin\phi_0/[r_1(1 + r_0^2) + r_0(1 + r_1^2)\cos\phi_0]. \tag{2}$$

Here, $\phi_0 = 4\pi n_0 l_0/\lambda$, $\phi_1 = 4\pi n_1 l_1/\lambda$, and λ is the oscillation wavelength in vacuum. The relations of λ vs $\tan\phi_1$ and $f(\phi_0)$ are shown in Fig. 5(b) with $l_0 = 3553\ \mu\mathrm{m}$, $l_1 = 400\ \mu\mathrm{m}$; $n_0 = 3.215$, $n_1 = 3.41$; $r_0 = 0.2$, $r_1 = 0.1$. Each cross point of

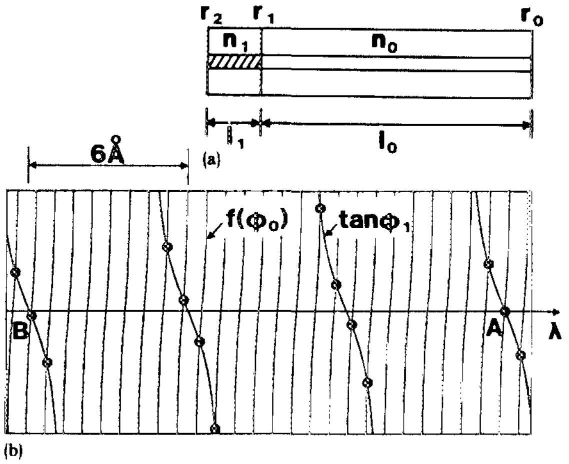

FIG. 5. (a) Model and device parameters of IPC lasers; (b) phase condition calculated for the long IPC laser. Each cross point of the curves corresponds to the solution of Eq. (1) and gives the wavelength of a longitudinal mode.

both curves gives the wavelength of a longitudinal mode. As l_0 is much longer than l_1 in this laser, there exist many modes that can be excited in the neighborhood of an active cavity mode. In this figure, however, only mode A is excited, because it has the least threshold gain.[9] Since the modes next to mode A have larger threshold gain and the mode with the second least threshold gain (denoted as mode B) exists with the spacing of about 18 Å, the longitudinal mode of the laser is transferred with this spacing.

Several improvements on the laser performance expected in this configuration are as follows: (1) narrowing of the spectral linewidth,[7,8] (2) reduction of the oscillation frequency chirping,[8–10] and (3) suppression of the intensity fluctuation (intensity noise).[9] Concerning the spectral linewidth narrowing, good result has already been obtained for the IPC lasers, and the minimum spectral linewidth measured so far was about 900 kHz at full width at half maximum by the delayed self-heterodyne beat measurement.[14] And for the chirping reduction, an oscillation frequency change of about 100 MHz/mA for 100-MHz sinusoidal current modulation has been obtained, which is considered to be the lowest value compared with the previously reported results that range from 0.11 to 1.5 GHz/mA.[15–17] Detailed results and discussions about these improvements will be reported elsewhere.

In conclusion, we have proposed the IPC lasers, which have a novel, easily producible SAIL guide structure. The long IPC laser with a 3.55-mm-long passive cavity was operated in a single longitudinal mode and showed the effects of oscillation frequency stabilization, which are the essential factors for future optical sources.

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Variable frequency picosecond optical pulse generation from laser diodes by electrical feedback

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High repetition rate picosecond optical pulse generation is achieved by providing electrical feedback (with and without external gain) to a self-pulsating laser diode. The feedback improves pulsation short-term stability (<25-kHz frequency jitter) and narrows the laser pulses (14 ps).

Different techniques have been demonstrated to generate very short optical pulses from laser diodes. These include mode-locked laser,[1,2] regenerative feedback,[3] optoelectronic feedback,[4] and mutual phase-locked loop.[5] In this letter, we demonstrate that *passive* and active electrical feedback is an effective way of generating picosecond optical pulses using a high-frequency laser diode specially treated to self-pulsate.[5]

The electrical equivalent circuit of a self-pulsating laser diode includes a negative resistance that leads to a microwave oscillation of electrical current through the diode,[6] which thus acts as a microwave oscillator. An electrical feedback to such a diode plays electrically a role similar to that played optically by an external optical cavity. The diode/circuit interaction significantly improves the optical pulse train regularity and reduces the pulse width. This is particularly noticeable in lasers made on semi-insulating substrate, where the small parasitic reactances lead to large microwave bandwidth.