Progress on the GaAlAs Ring Laser Gyroscope

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The aim of the work is the development of a semiconductor integrated version of the electrooptical gyroscope. To this end, the design criteria, the fabrication process and the experimental characterization of a large radius semiconductor ring laser are reported. Evidence is shown of the negative influence of output waveguide reflectivity on the spectral behaviour of conventional ring lasers. The P-I curve of a ring laser gyro structure with integrated photodiode is reported for the first time.

1. Introduction

A NEW APPROACH to the electrooptical gyroscope, based on a semiconductor ring laser, has recently been proposed [1]. This solution allows for a very compact realization, much smaller than the well-known RLG (Ring Laser Gyro) and FOG (Fiber Optic Gyro) [2, 3], and should offer a better sensitivity with respect to other recently proposed small-sized gyroscopes, i.e. the passive integrated optical gyro [4] and the micromachined gyro [5]. Recent research work [6] has gained a deep insight into the design and fabrication of semiconductor ring lasers for optical communications, which now appear as mature areas. The application of the semiconductor ring laser as a gyroscope requires particular features, such as large enclosed area, narrow linewidth, single-mode operation [1], not yet investigated in a systematic way.

In the present work we report progress on the design, fabrication and characterization of large-radius ring lasers and of a prototype version of the integrated ring laser gyroscope (IRLG), for which the functions of counter-propagating mode recombination and of signal detection are integrated on the same substrate.

2. Technology

Conventional fabrication methods for narrow ridge lasers (2 μm) feature two photolithographic steps, the second one (for window opening in the insulating layer) requiring extremely critical mask alignment for the case of large ring structures with diameter up to 3 mm. To overcome this problem, a self-alignment process (shown in Figure 1) has been developed [7], in which a single photolithographic step is performed for both ridge and window definition. After development (Figure 1A), the photoresist is postbaked to harden it, and it is directly used as a dry-etch mask (Figure 1B). In this dry-etching step no damage of the photoresist is observed and the ridge sidewall quality is the same as that obtained with the conventional procedure. The SiO_2 insulating layer is then deposited using an e-gun evaporator which yields a very directional deposition (Figure 1C), differently from the PCVD deposition which is isotropic. The SiO_2 layer on the top of the ridge is then lifted-off by dissolving the photoresist in acetone (Figure 1D). To improve this lift-off, a fast wet-etching of few tens of a nanometers in a solution of water:citric acid:hydrogen peroxide (30 : 30 : 1) is carried out to create a slight undercut on the ridge. This etching has the advantage of selectively etching GaAs and being inert in presence of AlGaAs. Since only the top-layer is made of GaAs, the etching undercuts only the top of the ridge and leaves the ridge height unchanged. Ohmic contacts are finally deposited on both sides of the sample and the device is annealed (Figure 1D).

The active region is made of two quantum wells of 10 nm thickness, separated by 10 nm. To keep the free-carrier absorption loss to a low value (necessary to achieve a narrow laser linewidth) the active zone is intrinsic, and the *p* and *n* regions are lightly doped ($5 \cdot 10^{17}$ cm^{-3}).

3. Devices

To test the adequateness of the technological process and to investigate functional aspects relevant for the

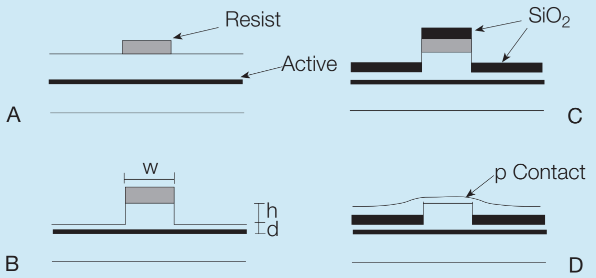

Figure 1 **Technological steps for device fabrication with the self-aligning process. A Resist development; B baked resist used as a dry-etch mask (relevant waveguide geometric dimensions are also shown); C insulating layer deposition; D contacting.**

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IRLG, several test devices have been designed, fabricated and characterized. In the following sections the characteristics of half-ring lasers, full-ring lasers and integrated gyros are reported.

3.1. Half-ring lasers

Half-ring lasers have been fabricated and tested to investigate the correctness of waveguide design. The optical field must propagate single-mode into the ring laser, and the bending loss must be as low as possible, since the laser cavity should have a high quality-factor (Q) in order to obtain a narrow linewidth. Also, light back-scattering must be reduced to a minimum to reduce the locking effect between the two counterpropagating modes which is detrimental for proper rotation sensing [1]. Hence, a trade-off must be found in determining both the ridge width and height. Large heights of the ridge improve the mode confinement, thus reducing bending loss, but enhance light back-scattering, because the semiconductor- SiO_2 interface beside the ridge is closer to the propagating mode. The chosen parameter values are the following: ridge width w = 2 µm; ridge height h = 0.9 µm; cladding layer thickness d = 0.2 µm (Figure 1B). With this geometry, concentric cleaved-end half-rings of different curvature radius (ranging from 0.3 mm to 1.5 mm) have been fabricated, and threshold characteristics have been measured. The usefulness of half-rings for design parameter evaluation is due to the fact that the modal power travel within the guide can be directly observed from the output facet, they require easier technological procedure and smaller wafer occupation area than the corresponding full-rings, which also require a waveguide coupler.

The measured threshold currents are reported in figure 2 as a function of curvature radius. The inset shows the half-ring arrangement. For small radii the thresholds are quite high due to increase of bending loss. For radii larger than 1 mm the characteristic approximates that of Fabry-Perot lasers, thus confirming that bending loss become negligible [8].

3.2. Ring lasers

Based on the transversal waveguide geometry defined above, 1 mm radius four-outputs ring-lasers have been fabricated. The inset of figure 3 shows the ring-laser structure. The two output active waveguides (with transversal geometry identical to the ring waveguide) are pumped by the same electrode used for the ring, and are cleaved at an angle of 6° to reduce spurious reflections from waveguide end-facets. One of the output waveguide also features non-contacted terminal ends, so that the unpumped regions help to drastically reduce facet reflectivity. This allows the investigation of the effect of the output waveguide on lasing characteristics.

The coupler between the ring and the output waveguides can be realized in different configurations: i.e. Y-junction, directional and Multi-Mode-Interference (MMI) coupler [9]. For the IRLG the directional coupler has been selected, because it allows coupling ratios well below 50%

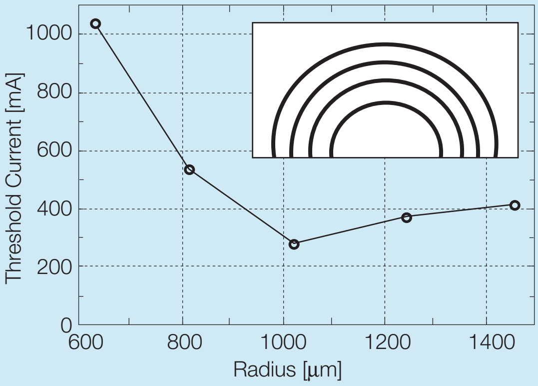

Figure 2 **Measured threshold currents of half-ring lasers for varying half-ring radius. Inset: half-ring lasers arrangement.**

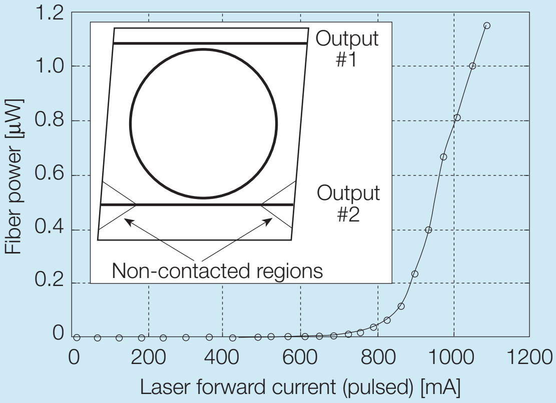

Figure 3 **P-I curve of conventional ring laser measured from output #1. Inset: ring laser structure.**

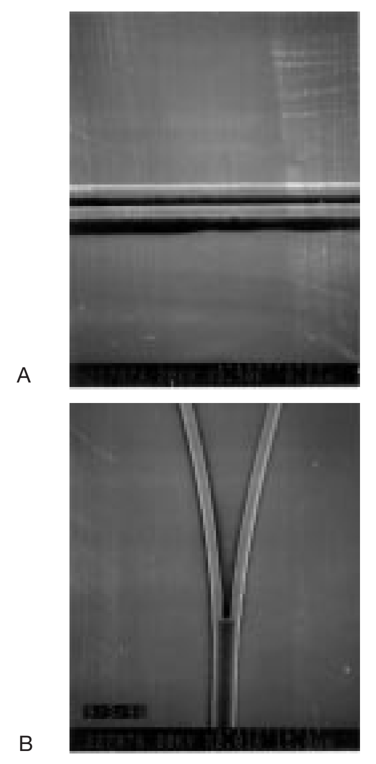

Figure 4 **A Scanning electron microscope picture of directional coupler between conventional ring laser waveguide and straight waveguide. B Scanning electron microscope picture of the tapered Y-junction for beams recombination in front of the integrated photodiode of the IRLG device.**

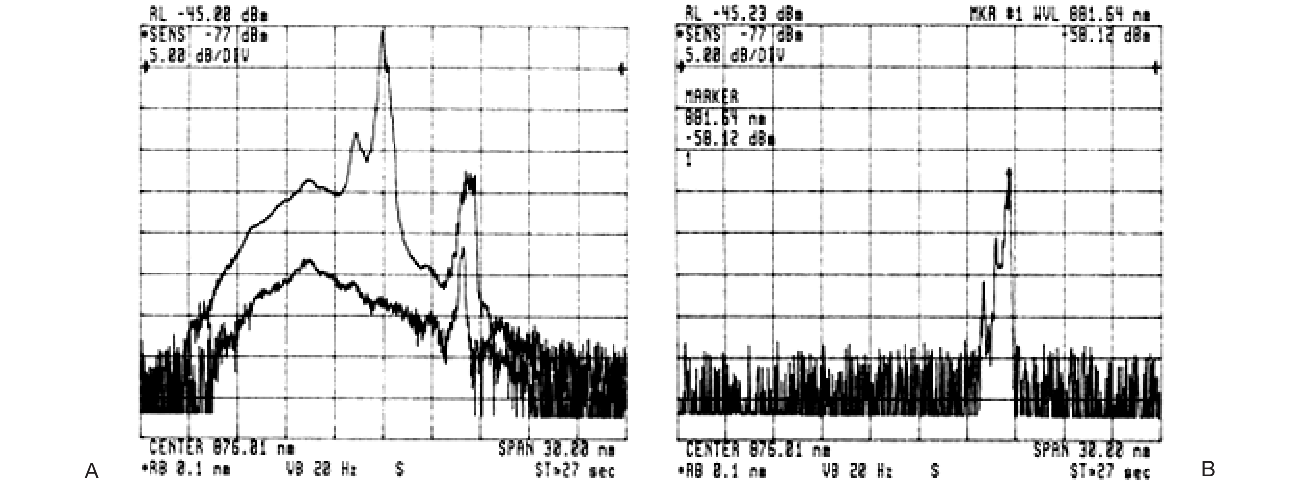

Figure 5 **Optical output spectra of conventional ring laser. A Output #1, lower trace I = 805 mA; upper trace I = 1104 mA. The wavelength of the ring laser mode is 881 nm. A spurious mode at 876 nm lasing in the straigth waveguide appears at higher current. B Output #2, I = 1104 mA. Despite the high current value, no spurious mode is observed, due to the unpumped terminal regions of straigth waveguide #2.**

(thus improving the cavity Q-factor) and reduces mode perturbation to a minimum. Indeed, from theoretical considerations the coupling ratio should be very small (in the order of 0.1 – 1%), obtained with a 2 μm gap between the waveguides. figure 4A shows a SEM picture of the coupling region.

In figure 3 we report the pulsed room temperature P-I characteristic obtained by collecting light with a multimode fiber from output #1, from which a 850 mA threshold is found. A very interesting result is shown in figure 5. Figure 5A reports the spectra collected at output #1 for two currents, namely a value below threshold (I_1 = 805 mA) and one above threshold (I_2 = 1104 mA). The spectra show that a mode starts lasing at 881 nm, and it is then overcame by a much more intense mode at 876 nm. This result, which could be at first attributed to the typical mode instability of long-cavity semiconductor lasers, is indeed caused by the output waveguide #1. In fact, the spectrum reported in figure 5B, collected at output #2 at current I_2 = 1104 mA, shows no evidence of the 876 nm mode. A possible explanation is the following: the 881 nm mode lases in the ring, while the 876 nm mode is oscillating in output waveguide #1. No oscillation is observed in output waveguide #2 because of the highly absorbing ends. Further confirmation comes from the lower threshold of the ring mode and from the lower wavelength of the mode lasing in the waveguide, as a consequence of gain peak shift with higher injection.

It can be concluded that conventional semiconductor ring lasers with very large radii are not best for the purpose of rotation sensing, due to the spurious lasing modes of the output waveguides that completely mask the mode lasing in the ring. Even if the waveguide ends were anti-reflection coated, the perturbations induced by the end reflections would negatively affect the detection of the beating between the counterpropagating modes lasing in the ring.

3.3 Laser-gyroscopes

For the purpose of rotation sensing an integrated ring laser structure has been designed and fabricated (the inset of Figure 6 shows a photograph of the device). The 1.5 mm radius ring is coupled to a curved output waveguide which is not terminated in air. Rather, the two output arms are combined together in a tapered Y-junction. The ring and the curved waveguides share the same contact, while the terminal tapered region has a separate electrode and must be reverse-biased to act as an integrated photodiode. This design allows for an easy recombination of the counterpropagating lasing modes, and avoids the problems caused by the angle-cleaved terminations and discussed in the previous section. Figure 4B shows a SEM photograph of the tapered Y-junction recombination region.

The pulsed room temperature lasing characteristic measured by the integrated photodiode is shown in figure 6. The photocurrent is amplified by a transimpedance amplifier and the integrated photodiode reverse bias is 2 V. The measurement yields a 600 mA threshold and good linearity of the characteristic even for high currents. Assuming a reasonable 1 A/W photodiode conversion factor, one finds

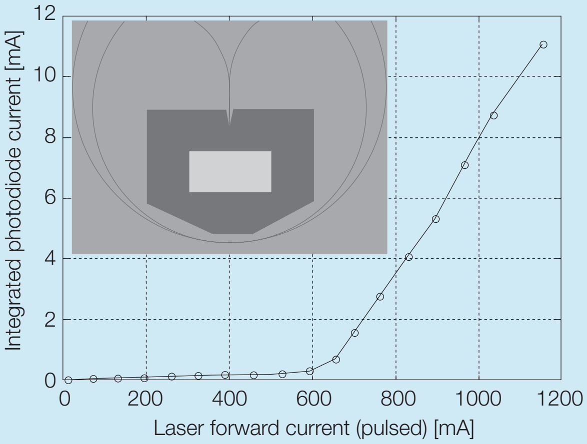

Figure 6 **Measured P-I curve of IRLG device. Light is detected by the integrated photodiode. Inset: picture of the fabricated IRLG device. It is shown the ring laser, the curved-waveguide output coupler, the Y-junction for beams recombination and the photodiode with separated contact.**

that optical power in excess of 10 mW is generated at 1100 mA. Unlike most ring lasers [9], this integrated device shows no kinks in the P-I characteristics. This is explained by the negligible reflections from output waveguides terminations and by the combination of the two outputs, that balance possible power exchanges between the two counterpropagating modes. Another evidence of correct device operation is given by spontaneous emission measurements made by means of a cleaved multi-mode optical fiber placed perpendicularly above the ring waveguide. This measurement showed a linear increase of collected power with injected current until the threshold value, where the characteristic becomes horizontal.
Experiments are in progress with the aim of detecting the Sagnac beating signal in the semiconductor ring laser, for the first time to our knowledge.

4. Conclusion

We have reported on the design, fabrication and experimental characterization of large radius semiconductor ring lasers aimed at the development of an integrated electrooptical rotation sensing device. The negative influence of the end-facet reflectivity of conventional angle-cleaved straight output waveguides on ring laser spectral characteristic has been noticed. A 1.5 mm radius ring laser with curved output waveguides terminated in a reverse-biased Y-junction integrated photodiode has been fabricated. The measured good lasing characteristic of this IRLG device is encouraging for future developments of the integrated electrooptical gyroscope.

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REFERENCES

[1] Donati S, Giuliani G, Sorel M: Proposal of a new approach to the electrooptical gyroscope: the GaAlAs integrated ring laser. *Alta Frequenza - Rivista di Elettronica*, vol. 9, n. 6, 1997, p. 61-63.

[2] Thomson BJ, ed.: Selected papers on fiber optic gyroscopes. *SPIE*, vol. MS-8, 1989.

[3] Knausenberger GE: Optical rotation rate sensors. In H. Sorg ed., *Advances in inertial navigation systems and components*, NATO series, 1982.

[4] Mottier P, Pouteau P: Solid state optical gyrometer integrated on silicon. *El. Lett.*, vol. 33, n. 23, 1997, p. 1975-1977.

[5] Voss R: Silicon micromachined vibrating gyroscopes. *SPIE*, vol. 3224, 1997, p. 62-73.

[6] Yu S, Krauss TF, Laybourn PJR: Multiple output semiconductor ring laser with high external quantum efficiency. *IEE Proc.-Optoelectron.*, vol. 144, n. 1, 1997, p. 19-22.

[7] Krauss TF, De La Rue RM, Laybourn PJR, Vögele B, Stanley CR: Efficient semiconductor ring lasers made by a simple self-aligned fabrication process. *IEEE J. Sel. Topics Quantum Electron.*, vol. 1, n. 2, 1995, p. 757-761.

[8] Nabiev RF, Francis D, Chang-Hasnain CJ: Lateral and longitudinal mode discrimination in index-guided circular ring semiconductor lasers. *IEEE Photon. Technol. Lett.*, vol. 5, n. 9, 1993, p. 975-978.

[9] Krauss TF, De La Rue RM, Laybourn PJR: Impact of output coupler configuration on operating characteristics of semiconductor ring lasers. *J. Lightwave Technol.*, vol. 13, n. 7, 1995, p. 1500-1506.

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