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Fibre ring cavity semiconductor laser

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Abstract. **This paper presents a study of semiconductor lasers having a polarisation maintaining fibre ring cavity. We examine the operating principle and report main characteristics of a semiconductor ring laser, in particular in single- and multiple-frequency regimes, and discuss its application areas.**

Keywords: *semiconductor optical amplifier, single-mode fibre, ring cavity.*

A semiconductor ring laser (SRL) is a semiconductor optical amplifier (SOA) closed with an optical fibre ring, which acts as a cavity. Interest in SRLs is aroused by the diversity of optical effects in semiconductors, the possibility of tuning the output of such lasers by simple means and their relatively low fabrication cost. SRLs can be used in optical communication systems, as components of various all-optical information processing devices [1–5], in navigation systems, in laser gyros [6–11], as master oscillators in rf and microwave generators [12–14] etc.

One important distinction of fibre cavity SRLs from other lasers is the possibility of incorporating a wide range of optical components into their cavity, which enables a variety of SRL-based devices to be easily designed and implemented. Such components include, among many others, fibre couplers, optical modulators, fibre Bragg gratings, optical isolators, optical circulators and Fabry–Perot etalons. Since fibre-pigtailed components are available commercially, such devices can readily be incorporated into a cavity.

The fibre cavity of an SRL can be of arbitrary length, from several centimetres to tens and even hundreds of kilometres. This in particular allows one to make SRLs having very long cavities, whose properties are worthy of special attention. A typical cavity length in SRLs is several metres, and their mode spacing is tens of megahertz, which allows SRLs to be used in microwave generators.

In contrast to linear-cavity lasers, where a standing wave is generated in the cavity, a travelling wave mode can take place in SRLs. Note that coexistence of two waves counterpropagating along a cavity is possible. This in particular allows one to employ an SRL as a key component of laser gyros utilising the Sagnac effect [6–11]. In the case of two counterpropagating waves, an SRL is in principle sensitive to rotations in the plane of its cavity. This shows up as different propagation conditions for the counterpropagating waves in the cavity and as a phase shift between the waves, which may cause a frequency difference between them, proportional to the angular rotation rate.

One important feature of the fibre cavity SRLs is their sensitivity to the polarisation of the light propagating along the fibre, which is in particular due to the polarisation sensitivity of their SOA. Owing to this property, SRLs can be employed as optical rotation sensors [15]. In addition, SRLs can be widely used as sensors owing to the high sensitivity of the fibre to various external influences, such as thermal, mechanical and magnetic [16].

SRLs possess a wide range of operation modes: unidirectional operation, which sets in when there is nonreciprocity in the cavity [17, 18], bidirectional operation and chaotic behaviour. The unidirectional operation of an SRL can be bistable, which allows one to switch the lasing direction and control the output spectrum of the laser by an external means [19, 20].

One obvious and natural feature of SRLs, which stems from their design, is that their emission is outcoupled by a fibre coupler. Depending on the type of fibre the cavity is made from, the SRL can operate in a multiple- or single-frequency regime. If standard single-mode fibre is used as the cavity, the SRL operates in the multiple-frequency regime. Polarisation-maintaining fibre enables single-frequency lasing.

The purpose of this work was to evaluate the performance of a polarisation maintaining fibre cavity SRL.

Figure 1 shows a schematic of the semiconductor ring laser and its components. The SRL comprises a semiconductor optical amplifier [21], polarisation-maintaining single-mode fibre forming a loop with the gain element, an optical

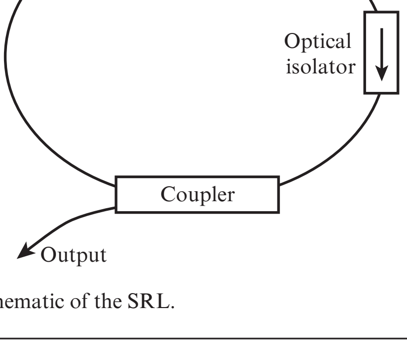

Figure 1. Schematic of the SRL.

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isolator and a coupler. The components are connected using FC/APC optical connectors and adapters. The optical isolator ensures unidirectional ring operation. The SRL beam is outcoupled from the cavity by a 50/50 fibre coupler.

The fibre used can preserve linear polarisation oriented along one of its axes (fast or slow) with an extinction ratio above 40 dB. The ability of such fibre to preserve the polarisation state is due to the mechanical stress induced by purpose-designed rods, which gives rise to birefringence along the fibre core.

When FC/APC connectors are placed at the fibre ends, the connector key should be aligned to the slow axis of the fibre. We used a passive fibre orientation method: visual observation of the position of the stress elements in the fibre cross section.

Figure 2 shows the power–current characteristic of the SRL. The threshold current for lasing was 70 mA. The output power was up to 12 mW at a pump current of 190 mA. Since the ring cavity consists of polarisation-maintaining fibre, the fibre and SOA form an interference polarisation comb filter (Lyot filter). Its operating principle is that, in such fibre, light is split into two waves, ordinary and extraordinary, linearly polarised in two mutually perpendicular planes. The two waves propagate along the fibre in the same direction but with different phase velocities, so on each cavity pass the waves acquire a phase difference (and, hence, a path length difference),

$$\delta = \frac{2\pi}{\lambda}(n_{\mathrm{e}} - n_{\mathrm{o}})L,$$

where n_{o} and n_{e} are the ordinary and extraordinary indices and L is the fibre length.

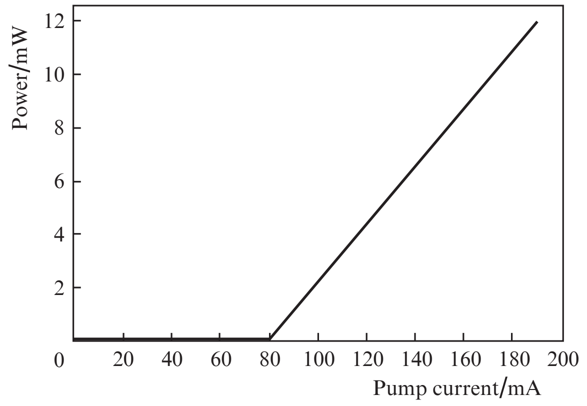

Figure 2. Power–current characteristic of the SRL.

Since their oscillations are mutually perpendicular, the ordinary and extraordinary waves cannot interfere and, for this reason, the light is elliptically polarised. When such light is directed to a polariser, only the components polarised in the same plane will be passed for both waves, i.e. oscillations in the same direction will be separated from the two coherent waves. These waves will interfere, depending on the path length difference acquired in the fibre. Therefore, the light intensity will depend on the phase difference acquired in the fibre by both waves. The SOA active element, which amplifies mostly only one polarisation, acts as a polariser.

The free spectral range is the separation between neighbouring transmission peaks of the filter:

$$\Delta\lambda = \frac{\lambda^2}{L(n_{\mathrm{e}} - n_{\mathrm{o}})}.$$

Figure 3 shows the optical spectrum of the SRL at a fibre cavity length of 1 m. Therefore, $\Delta\lambda = 4.8$ nm and the gain needed for lasing is ensured for only one transmission peak of the filter. The emission linewidth is 0.012 nm, which

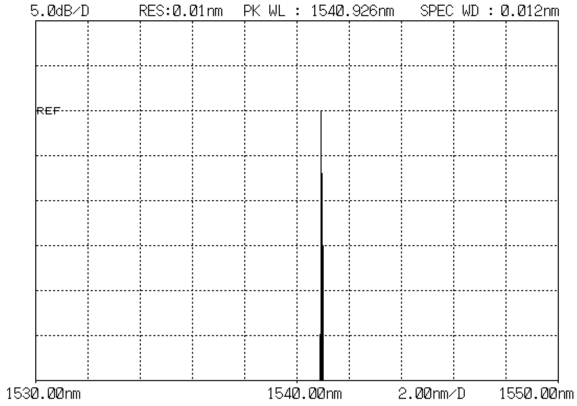

Figure 3. Optical spectrum of the SRL at a polarisation maintaining fibre length of 1 m.

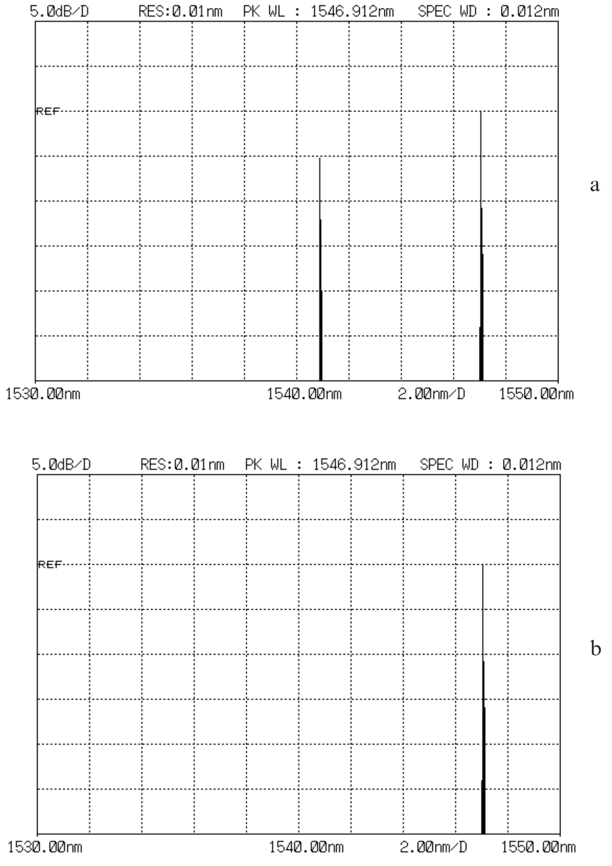

Figure 4. Optical spectrum of the SRL at a fibre length of 1 m and gain element temperatures of (a) 35 and (b) 40 °C.

approaches the resolving power of the spectrum analyser used.

Raising the temperature of the SOA shifts the gain band to longer wavelengths. At a temperature of 35 °C, the spectrum shows two emission lines, corresponding to two neighbouring transmission peaks of the filter (Fig. 4a). At higher temperatures, the necessary gain is only reached for the longer wavelength peak (Fig. 4b).

Increasing the length of the polarisation-maintaining fibre reduces the free spectral range, and simultaneous lasing on two or more lines corresponding to transmission peaks of the filter becomes possible. Figure 5 shows the optical spectrum of the SRL at a fibre length of 10 m. At this fibre length, we have $\Delta\lambda = 0.5$ nm and lasing occurs simultaneously on nine lines (at a 3-dB flatness).

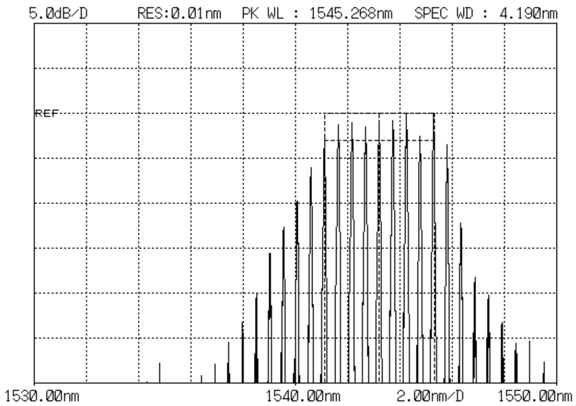

Figure 5. Optical spectrum of the SRL at a polarisation maintaining fibre length of 10 m.

The SRLs commercially available at present have a fibre cavity several millimetres to hundreds of metres in length. This allows them to find more and more applications, in particular as single- and multiple-frequency laser oscillators.

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