Quantum Electronics **38** (8) 707 – 709 (2008)

LETTERS

PACS numbers: 42.82.Et; 42.55.Px; 42.60.Da
DOI: 10.1070/QE2008v038n08ABEH013917

Active composite waveguides with a suppressed competition of optical modes

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***Abstract*. The possibilities of separating the fundamental optical mode in composite waveguides by selecting the structure of amplifying regions are analysed. Conditions are presented under which the fundamental mode preserves the highest gain at any saturation.**

Keywords: *optical waveguide, amplification, selection and competition of optical modes.*

Optical waveguides are widely used in laser technologies including diode and fibre lasers. Conventionally, waveguides confine laser radiation and can contain an amplifying medium. Because the output power, generally speaking, is proportional to the area of the pumped region, the waveguide dimensions should be large. A high quality of output radiation is obtained in lasers generating only one transverse mode. The aperture of a single-mode waveguide is limited by the condition of maintaining one mode and can increase only due to a decrease in the refractive index step Δn at the waveguide boundary. For $\Delta n = 10^{-3}$ the maximum diameter of a single-mode glass circular waveguide is 14λ, where λ is the laser wavelength.

It was assumed to further increase the output power by passing to systems of coupled active waveguides [1]. Investigations of diode lasers (DLs) showed [1] that this approach cannot provide a large increase in the power of a diffraction beam, while the system becomes significantly more complicated. The next step consisted in a passage to antiwaveguide structures in which the amplification occurred in regions with a reduced refractive index and generation was obtained on leaky modes. This approach was developed for surface-emitting [1] and vertical-cavity surface-emitting DLs [2], as well as for fibre lasers [3, 4]. Experiments showed that in this case the improvement of laser characteristics is restricted by the instability of the single-mode regime caused by the competition of higher-order modes. The inhomogeneous gain saturation for the fundamental mode leads to a relative increase in the gain of other modes and their participation in lasing.

We show in this paper by a number of examples that the gain of the fundamental guided mode in a composite waveguide, in which amplification occurs in regions with a reduced refractive index, remains the highest upon the gain saturation. This means that at any excess over the threshold, single-mode lasing will be stable until nonlinear effects of some other nature take place.

To illustrate the main idea of our paper, consider a system of two parallel planar single-mode waveguides (Fig. 1a). The calculation of modes of surface-emitting DLs in the effective refractive index approximation is reduced to this problem [5]. One can demonstrate that if the amplification is concentrated between waveguides in this system, the gain of the symmetric (fundamental) mode is higher at any saturation than that of the antisymmetric

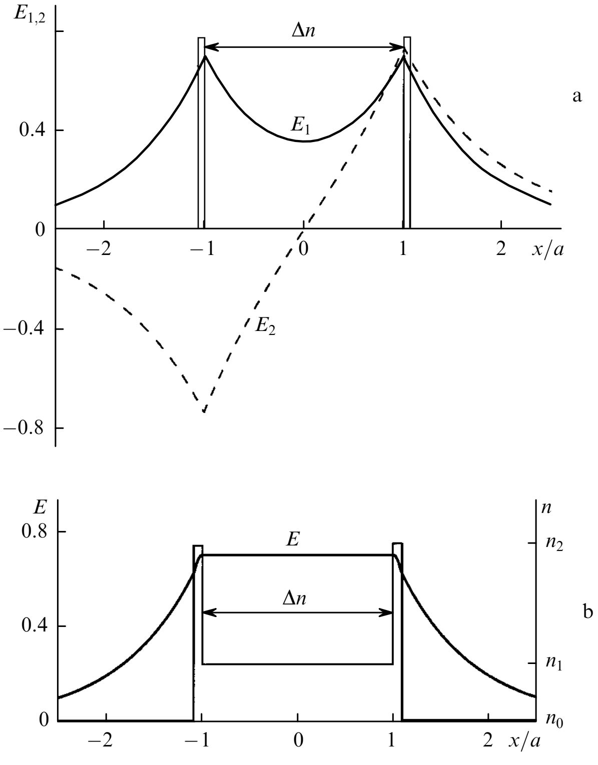

Figure 1. Profiles of the refractive index and the fundamental mode field of a planar composite waveguide formed by a pair of coupled waveguides (dashed curve shows an odd guided mode) (a) and a waveguide with an increased refractive index in the internal region (b). The amplification is concentrated in the region $|x| < a$.

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Received 6 June 2008
Kvantovaya Elektronika **38** (8) 707 – 709 (2008)
Translated by I.A. Ulitkin

mode. Intuitively this behaviour of the saturated gain is clear. The intensity of the fundamental mode between the waveguides is considerably higher than that of the antisymmetric guided mode. This fact was earlier pointed out in [6], where a high lasing stability at the symmetric mode was experimentally demonstrated. However, this system has an obvious disadvantage: the intensity maxima of a lasing mode are located inside the waveguides, while the field intensity at the centre of the amplification decreases with increasing the distance $2a$ between the waveguide. Thus, as the laser aperture is increased, the lasing threshold increases, while the lasing efficiency decreases. The increase in a is mainly limited by the competition between the fundamental and leaky modes; the losses in the latter decrease with increasing a, while the mode small-signal gain is almost constant. In the limit of two thin waveguides, we can find the condition under which the small-signal gain of the fundamental mode is higher than the small-signal gain of the leaky mode minus radiation losses:

$$32\pi^2 n_0^3(\Delta n)^2 g_0 a \leqslant \left(\frac{\lambda}{2a}\right)^3\left(\frac{\lambda}{\Delta}\right)^2, \qquad (1)$$

where n_0 is the refractive index of the environment; g_0 is the small-signal gain of the medium; and Δ is the waveguide thickness. The product $g_0(\Delta n)^2$ required to realise condition (1) strongly depends on λ and rapidly (as $1/a^4$) decreases with increasing the distance between the waveguides. For example, $g_0 \leqslant 2.75 \times 10^4 a^{-4}$ for $\lambda = 1$ μm, $\Delta n = 10^{-3}$, $\Delta = 2$ μm and $n_0 = 3.3$ (here g_0 is measured in cm^{-1} and a – in μm).

The competition between modes can be substantially reduced by producing a higher refractive index in the central part than in the cladding (Fig. 1b). If the values of two refractive index steps and thickness Δ of each waveguide from the pair are selected so that the relation

$$\tan[k\Delta(n_2^2 - n_1^2)^{1/2}] = \left(\frac{n_1^2 - n_0^2}{n_2^2 - n_1^2}\right)^{1/2} \qquad (2)$$

is fulfilled, where $k = 2\pi/\lambda$; n_1 and n_2 are the refractive indices of the internal region and side waveguides, respectively, the fundamental mode intensity in the central region will be constant. In this case, the gain saturation is spatially uniform. Therefore, if the small-signal gain for the fundamental mode is higher than that for other modes, this inequality holds true at any saturation level of the fundamental mode. The saturation caused by other modes is accompanied by a relative increase in the gain of the fundamental mode. Note that the width of the central part does not affect relation (2). The number of guided modes in a composite waveguide increases with increasing a. If the gain is distributed along the entire width $2(a + \Delta)$, the small-signal gain of the fundamental mode is higher than that of all other guided modes. Because leaky mode losses decrease with increasing a, the danger of competition from leaky modes remains, although the conditions for their suppression become easier. Note that the width of the axial peak in the far field for the lowest leaky mode is close to the width of the same peak for the fundamental mode, therefore, the appearance of lasing at the fundamental leaky mode does not significantly change the quality of the output total beam.

Circular waveguides are of much interest for fibre lasers and vertical-cavity diode lasers. Concepts considered above by the example of planar waveguides are apparently applicable in radial structures with a cylindrical symmetry. In particular, a ring waveguide of thickness Δ surrounding the active core of radius a is a counterpart of the structure presented in Fig. 1a. Note that this structure with pumping in the central part was earlier considered in [7] for vertical-cavity DLs. The authors of [7] analysed the properties of the leaky mode because the small-signal gain of the guided mode for a ring of a large radius is smaller than the difference in the gains and losses of the leaky mode. It is the involvement of the leaky mode in lasing that prevents lasing at the fundamental guided mode.

An increase in the refractive index in the central part of the waveguide with respect to the external cladding as in the case of the plane geometry drastically changes the situation. The selection of the combination of refractive index steps and the ring thickness allows one to generate the fundamental mode with a constant intensity in the central part. Expression (2) can be also used in this case if the radius of the central part is much larger than the ring thickness ($a \gg \Delta$). The effect of the proposed modification of the circular composite waveguide structure on the mode composition and mode competition can be illustrated by the example of the structure with $a = 18$ μm and $\Delta = 2$m (the area of the generated mode exceeds 1200 μm^2). The refractive index steps in the central part of the waveguide and in the ring with respect to the refractive index of the

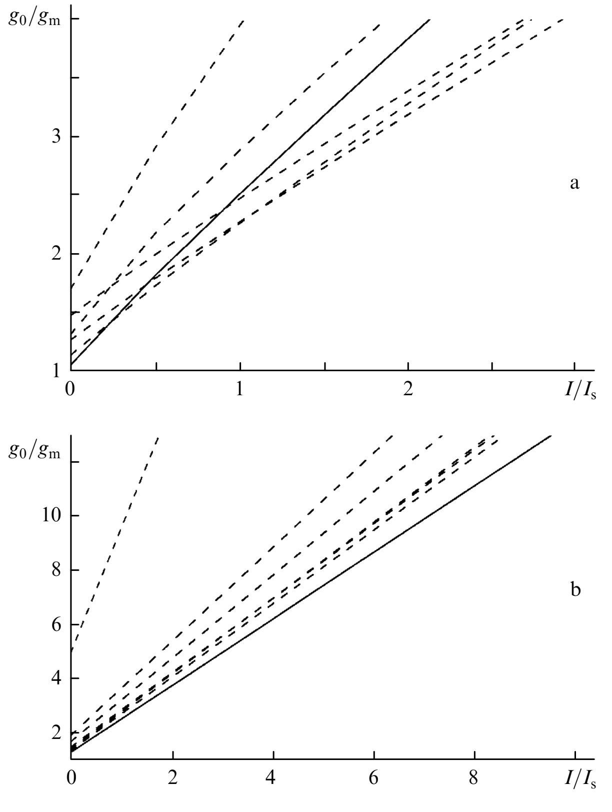

Figure 2. Inverse mode gains of the fundamental mode (solid curves) and of guided higher-order modes (dashed curves) as functions of the fundamental mode intensity on the axis of the active waveguide with $n_0 = 1.456$, $n_1 = n_2 = 1.457$ (a) and $n_0 = 1.456$, $n_1 = 1.457$, $n_2 = 1.4584$ (b).

cladding are taken equal to 10^{-3} and 2.4×10^{-3}, respectively, according to the estimates by expression (2).

The effect caused by modification of the active waveguide structure is seen when the competition of modes in a circular waveguide of radius 20 μm and $\Delta n = 10^{-3}$ and in the composite waveguide under study is compared. By neglecting the polarisation effects in both waveguides eight guided modes have been found numerically and their mode gains ($g_{\rm m}$) have been calculated by averaging with the intensities of the corresponding modes. Apart from the small signal gain, we have found the gains saturated by the fundamental mode. The expression for a saturated gain of the medium was taken in the simplest form: $g = g_0/(1 + I/I_{\rm s})$, where I and $I_{\rm s}$ are the intensities of the fundamental mode and saturation, respectively. The dependences of $g_0/g_{\rm m}$ on $I/I_{\rm s}$ are presented in Fig. 2 for a standard and a composite waveguides. One can see that in a conventional circular waveguide, the gain for the fundamental mode becomes equal to the gain for two angular modes for $I/I_{\rm s} \approx 0.25$, while in a composite waveguide the competition of all highest modes is completely suppressed and the dependences of $g_{\rm m}^{-1}$ on the fundamental mode intensity is close to straight divergent lines. When the refractive index of the ring waveguide is slightly varied, the competition between all the maintained modes is still suppressed. Additional calculations of a fibre amplifier with the input beam containing leaky modes have shown that these modes do not play any role.

The discussed active multimode waveguides with a suppressed competition of optical modes, which have an increased mode aperture, can serve as elements of a system of optically coupled lasers.

Acknowledgements. This work was supported by the Russian Foundation for Basic Research (Grant Nos 07-02-01112a and 07-02-12166-ofi). The authors thank D. Botez and L.J. Mawst for providing a reference to [6].

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