OPTICAL WAVEGUIDES

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Structure of the core – cladding interface and radiation losses in hollow planar Bragg waveguides

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***Abstract*. A planar Bragg waveguide with a hollow core is considered. Analytic dependences of the mode properties of the waveguide on its geometrical parameters are presented. By using these dependences, optimal parameters of the Bragg waveguide are determined. The dependence of the properties of the waveguide modes on the structure of the internal boundary of its cladding is considered for the first time. In addition, the dependence of the waveguide radiation losses on the number of its layers is considered for wavelengths 1.55, 10.6 and 0.245 μm of practical interest.**

Keywords: *Bragg waveguide, radiation losses, microstructure optical fibres.*

1. Introduction

Multilayer structures are widely used in fundamental and applied physics. Bragg waveguides, i.e. waveguides with multilayer walls, attract attention of researchers first of all because their spectrum contains many modes. This spectrum can be controlled by changing the waveguide geometry by varying the angle of a guided mode, shifting the zero dispersion region, producing waveguides with an increased mode area, and concentrating the mode field in the hollow core. This reduces, in particular, nonlinear effects, bending and fundamental losses and enhances the radiation resistance, etc.

The above properties stimulate the rapid development in the manufacturing technology of Bragg waveguides. At present, the number of layers in the periodic structure can achieve several hundreds [1 – 4]; therefore, of interest is the limiting possibilities of Bragg waveguides with a great number of layers. In this paper, we will consider radiation losses (determined by radiation modes carrying energy out of the waveguide core) and the possibility of concentrating the field in the waveguide core. Of special interest is hollow-core waveguides [5], to which special attention is paid in this paper. The analysis is performed based on solutions of coupled-wave equations, which give a complete description of the Bragg mode structure and are of interest for different applications. In particular, the analytic solution of the dispersion equation makes it possible to select the waveguide parameters and geometry providing optimal mode properties. We also studied the influence of the core – cladding interface on the field structure in the core and cladding.

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2. The dispersion equation and radiation losses

Consider a planar Bragg waveguide with the core of 'radius' a (the term 'radius' is used for convenience by analogy with the cylindrical case) and permittivity ε_0 (Fig. 1). The cladding of radius b consists of alternating layers of two equally-thick materials with the permittivities $\varepsilon_{\min}$ and $\varepsilon_{\max}$. Bragg modes can be described with good accuracy by substituting the permittivity step profile in Fig. 1 by the first term of its Fourier expansion. Then, the permittivity of such a waveguide has the from

$$\varepsilon(x) = \begin{cases} \varepsilon_0, \ x < a, \\ \varepsilon + 2B\cos[2q(x-a) - \varphi], \ a < x < b, \\ \varepsilon_1, \ x > b, \end{cases} \quad (1)$$

where ε_0 is the core permittivity; ε is the mean permittivity of the layered cladding; $q = \pi/d$; $B = (\varepsilon_{\max} - \varepsilon_{\min})/\pi = \delta\varepsilon/\pi$; d is the structure period; l is the distance from the core – cladding interface to the centre of the first layer with the maximum refractive index; ε_1 is the permittivity in the

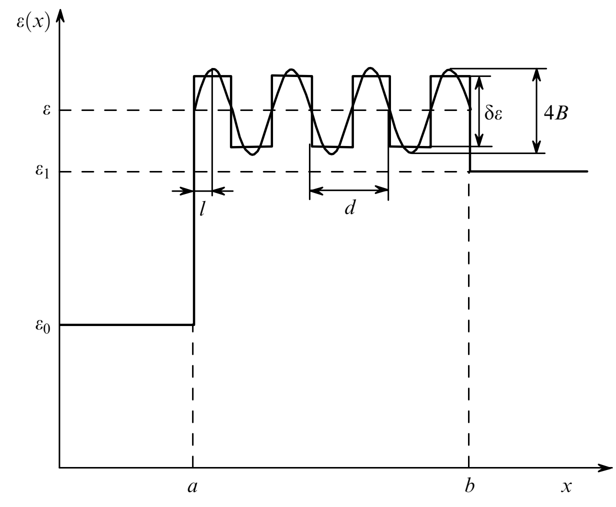

Figure 1. Transverse profile of the waveguide permittivity.

external cladding; and $\varphi = 2\pi l/d$ is the phase of a grating associated with the periodic cladding (the parameter characterising the structure of the core – cladding interface).

For modes propagating along the z axis, the field in waveguide (1) has the from $E(x,z) = u(x)\exp(ik\tilde{v}z)$, where $\tilde{v}$ is the effective refractive index and k is the wave number. The imaginary part $\operatorname{Im}\tilde{v} > 0$ is responsible for losses.

The wave equation

$$u''(x) + k^2\left[\varepsilon(x) - \tilde{v}^2\right]u(x) = 0 \tag{2}$$

has the solution [6]:

$$u(x) = \begin{cases} \cos[k(\varepsilon_0 - \tilde{v}^2)^{1/2}x], & x < a, \\ c_1u_1(x) + c_2u_2(x), & a < x < b, \\ T\exp[ik(\varepsilon_1 - \tilde{v}^2)^{1/2}x], & x > b. \end{cases} \tag{3}$$

Here,

$$u_1(x) = \exp[-\tilde{\mu}(x-a)]\{\exp[iq(x-a)] + \tilde{r}\exp(i\varphi)\exp[-iq(x-a)]\}; \tag{4}$$

$$u_2(x) = \exp[\tilde{\mu}(x-a)]\{\tilde{r}\exp(-i\varphi)\exp[iq(x-a)] + \exp[-iq(x-a)]\};$$

$$\tilde{\mu} = \frac{Bk^2(1-\tilde{D}^2)^{1/2}}{2q}; \quad \tilde{r} = i\left(1-\tilde{D}^2\right)^{1/2} - \tilde{D};$$
$$\tilde{D} = \frac{\varepsilon(\tilde{v}^2 + q^2/k^2)}{B}; \tag{5}$$

c_1, c_2, T are complex constants.

Solution (3) was derived in the region $a < x < b$ by the method of coupled waves in the slowly varying-amplitude approximation (see [6]), which are valid for

$$|\tilde{\mu}| \ll q, \quad B \ll \varepsilon - \varepsilon_0. \tag{6}$$

For hollow waveguides, condition (6) is fulfilled almost always. It is under this condition that the structure consisting of layers of equal thickness [see (1) and Fig. 1] is optimal from the point of view of radiation losses. If condition (6) is not fulfilled, the optimal is the quarter-wave structure (see [7], [8]), in which layer thicknesses differ.

By joining the found solutions at the boundaries $x = a$ and $x = b$, we obtain dispersion equations:

$$k(\varepsilon_0 - \tilde{v}^2)^{1/2}\tan[k\left(\varepsilon_0 - \tilde{v}^2\right)^{1/2}a] = \left.\frac{u_1' + c_2u_2'/c_1}{u_1 + c_2u_2/c_1}\right|_{x=a}, \tag{7}$$

$$\frac{c_2}{c_1} = \left.\frac{ik\left(\varepsilon_1 - \tilde{v}^2\right)^{1/2}u_1 - u_1'}{ik\left(\varepsilon_1 - \tilde{v}^2\right)^{1/2}u_2 - u_2'}\right|_{x=b}. \tag{8}$$

For $b \to \infty$, equations (2), (7), and (8) describe the Bragg waveguide with an infinite number of layers, which was considered for $\varphi = 0$ in [6]. For $\varphi \neq 0$, the field in the waveguide has the from

$$u(x) = \cos kx\left(\varepsilon_0 - v^2\right)^{1/2}, \quad x < a,$$

$$u(x) = \frac{\left[(\varepsilon_0 - v^2)/(\varepsilon - v^2)\right]^{1/2}\exp(i\psi)}{2\left[\sin 2\psi + \cos^2\psi(\varepsilon_0 - v^2)/(\varepsilon - v^2)\right]^{1/2}} \times \exp[-\mu(x-a)]\{\exp(-i\psi)\exp[iq(x-a)] + \exp(i\psi)\exp[-iq(x-a)], \quad x < a, \tag{9}$$

where

$$r = i\left(1-D^2\right)^{1/2} - D = \exp(i\chi); \quad \mu = \frac{Bk^2\left(1-D^2\right)^{1/2}}{2q};$$
$$D = \frac{\left[\varepsilon - (v^2 + q^2/k^2)\right]}{B}; \quad \psi(v) = \frac{\varphi + \chi(v)}{2};$$
$$\chi = \arccos(-D). \tag{10}$$

The effective refractive index v is derived from the dispersion equation (see [6]):

$$k\left(\varepsilon_0 - v^2\right)^{1/2}\tan\left[ka\left(\varepsilon_0 - v^2\right)^{1/2}\right] = -\left.\frac{u_1'}{u_1}\right|_{x=a} = -q\tan\psi(v), \tag{11}$$

which can be obtained from (7), (8) for $b \to \infty$. In this case, unlike (4), (5), quantities v, μ, and D become real. In particular, μ describes the field decay into the cladding, while D determines the position of modes with respect to the centre of the Bragg reflection band corresponding to $D = 0$.

Dispersion equation (11) can be also written in the form:

$$a = \frac{1}{k\left[q^2/k^2 - (\varepsilon - \varepsilon_0) + DB\right]^{1/2}}\left(\pi n - \arctan\left\{\frac{q}{k\left[q^2/k^2 - (\varepsilon - \varepsilon_0) + DB\right]^{1/2}}\tan\frac{\varphi + \chi(D)}{2}\right\}\right), \tag{12}$$

where n is the number of zeros of the function $u(x)$ in the region $x < a$.

Equation (12), unlike (11), determines the 'detuning' D related to the effective refractive index v according to (10).

We will seek the solution of dispersion equation (7) for the finite b in the form $\tilde{v} = v + \delta v$, where $\delta v \to 0$ for $b \to \infty$. Then, for large enough b, we obtain from (7) and (8):

$$\operatorname{Im}\delta v = \frac{B}{v}\left(\frac{\varepsilon - v^2}{\varepsilon_1 - v^2}\right)^{1/2}(1-D^2)^2 \times \exp\left[-\frac{\pi B}{\varepsilon - v^2}N(1-D^2)^{1/2}\right]\left\{1 + \frac{B(1-D^2)^{3/2}}{\varepsilon_0 - v^2} \times \left[qa\left(\sin^2\psi + \frac{\varepsilon_0 - v^2}{\varepsilon - v^2}\cos^2\psi\right) - \frac{\sin 2\psi}{2}\right]\right\}^{-1} \tag{13}$$
$$\times\left\{\cos^2\left[q(b-a) + \frac{\chi}{2}\right] + \frac{\varepsilon - v^2}{\varepsilon_1 - v^2}\sin^2\left[q(b-a) + \frac{\chi}{2}\right]\right\}^{-1},$$
$$\delta v \ll v,$$

where N is the number of periods in the cladding structure. For the hollow core and $\varepsilon_1 \approx \varepsilon$ in (13), the term $(\varepsilon - v^2)/(\varepsilon_1 - v^2)$ is approximately equal to unity. Then, the expression in the last braces in (13) is unity.

Note that expression (13) is valid only for $c_2/c_1 \ll 1$. This relation is fulfilled when the exponent in (13) is sufficiently large:

$$\frac{\pi B}{\varepsilon - v^2} N(1 - D^2)^{1/2} \gg 1. \tag{14}$$

The losses in dB per unit length can be estimated from the expression

$$\kappa = \frac{2k \operatorname{Im} \delta v}{\ln 10}. \tag{15}$$

3. Mode properties and waveguide optimisation

In this section, we will determine the parameters of a Bragg waveguide (including its structure period, phase, and radius) optimising its optical properties (field decay in the cladding, field concentration in the core, field value at the core–cladding interface, and radiation losses) and will find the criterion for single-mode propagation (i.e. we will find the maximum radius at which the waveguide remains single-mode one). It turns out in this case, that it is sufficient to consider a waveguide with the infinite number of layers in the cladding ($N = \infty$). This concerns all the optical properties except radiation losses, which are absent in the case of the infinite number of layers. However, as shown in section 2, the radiation losses in the case of a sufficiently large number of layers also can be expressed through the parameters of a waveguide with infinite walls [see (13)].

In this connection, consider in detail the mode structure of a Bragg waveguide with the infinite number of layers ($N = \infty$). We will follow paper [6], where the case $\varphi = 0$ was studied. The dispersion equation and formula to find the fields of waveguide modes with $\varphi \neq 0$ are presented in section 2 [see (9) and (11)]. In principle, they allow one to determine all its optical properties. The decay rate μ of the field into the cladding and radiation losses are determined by expressions (10) and (13).

One can also easily obtain from (9) expressions for the field at the core–cladding interface:

$$u(a) = \left(\frac{\varepsilon_0 - v^2}{\varepsilon - v^2}\right)^{1/2} \cos\frac{\varphi + \chi(v)}{2} \left[\sin^2\frac{\varphi + \chi(v)}{2} + \frac{\varepsilon_0 - v^2}{\varepsilon - v^2}\cos^2\frac{\varphi + \chi(v)}{2}\right]^{-1/2} \exp\left[\mathrm{i}\frac{\varphi + \chi(v)}{2}\right] \tag{16}$$

and for the field concentration in the core

$$\Gamma = \frac{1}{1 + A}, \tag{17}$$

where

$$A = \frac{\int_a^\infty |u(x)|^2 \mathrm{d}x}{\int_0^a |u(x)|^2 \mathrm{d}x} = \frac{\varepsilon_0 - v^2}{\varepsilon - v^2}\left\{2\mu a\left[\sin^2\frac{\varphi + \chi(v)}{2} + \frac{\varepsilon_0 - v^2}{\varepsilon - v^2}\cos^2\frac{\varphi + \chi(v)}{2}\right]\left[1 + \frac{\sin 2ka(\varepsilon_0 - v^2)^{1/2}}{2ka(\varepsilon_0 - v^2)^{1/2}}\right]\right\}^{-1}$$

is the ratio of the field energy in the cladding to the field energy in the core.

Thus, expressions (10), (13), (16), and (17) describe the main optical properties of waveguide modes.

If the mode is at the centre of the forbidden gap, i.e. the detuning $D = 0$ ($\chi(v) = \pi/2$), the escape rate of the field into the cladding μ proves to be maximal [see (10)]. Such a mode is called central. One can easily see from expressions (13) and (17) that the central mode is also most advantageous from the point of view of radiation losses and the field concentration in the core. The condition $D = 0$ means that the effective refractive index is

$$v = \left(\varepsilon - \frac{q^2}{k^2}\right)^{1/2}. \tag{18}$$

Due to dispersion equation (11), this leads to relation between the geometrical parameters of the waveguide:

$$a = \frac{1}{k\left[q^2/k^2 - (\varepsilon - \varepsilon_0)\right]^{1/2}} \times \left(\pi n - \arctan\left\{\frac{q}{k\left[q^2/k^2 - (\varepsilon - \varepsilon_0)\right]^{1/2}}\tan\left(\frac{\varphi}{2} + \frac{\pi}{4}\right)\right\}\right). \tag{19}$$

The next most significant parameter for the waveguide optimisation is the phase φ, which characterises the structure of the core–cladding interface [see (1) and Fig. 1]. By analysing expression (17) for the central mode, we can easily see that the maximum concentration of the field is achieved for $\varphi = \pi/2$, when the refractive index of the first layer is maximal and its thickness is equal to half the structure period. Note that in this case the field at the core–cladding interface vanishes. This circumstance can be used for designing fibres to minimise losses caused by light scattering from residual surface inhomogeneities of the core after the fibre drawing [5].

For the optimal structure of the cladding boundary under study ($\varphi = \pi/2$), relation (19) (for the first mode) takes the form

$$a = \frac{\pi}{2k\left[q^2/k^2 - (\varepsilon - \varepsilon_0)\right]^{1/2}}. \tag{20}$$

Then, by using (17) and (13), we obtain the field energy fraction in the cladding

$$A = \frac{\pi^2}{4q^3a^3B}\frac{q^2}{k^2}, \tag{21}$$

and radiation losses

$$\operatorname{Im}\delta v = \frac{B}{(\varepsilon - q^2/k^2)^{1/2}(\varepsilon_1 - \varepsilon + q^2/k^2)^{1/2}}\frac{q}{k} \times \frac{\exp(-\pi Bk^2N/q^2)}{1 + 1/A}, \tag{22}$$

where the radius a is determined by expression (20).

Let us find the maximum radius of a single-mode waveguide in which the first mode is the central mode. The waveguide radius a (20) and the propagation constant v (18) for the fixed values of λ, ε, ε_0 depend only on the ratio q/k. In the general case, the domain of the mode existence is determined by the inequalities $-1 < D < 1$ and $0 < v^2 < \varepsilon_0$. If we fix the parameters q, λ, ε, ε_0 and increase the radius a, the mode can appear either for $v = 0$ (and large enough B) or for $D = 1$.

The radius, at which the second mode appears (for $D = 1$), is

$$a = \frac{1}{k\left[q^2/k^2 - (\varepsilon - \varepsilon_0) + B\right]^{1/2}} \times \left(\pi + \arctan\left\{\frac{q}{k\left[q^2/k^2 - (\varepsilon - \varepsilon_0) + B\right]^{1/2}}\right\}\right). \quad (23)$$

The simultaneous fulfilment of conditions (20) and (23) yields the maximum radius and period $d = \pi/q$ of the single-mode waveguide whose first mode is central.

For $B \ll 1$, we can write:

$$\frac{q^2}{k^2} - (\varepsilon - \varepsilon_0) = \frac{B}{8}, \quad (24)$$

$$v^2 = \varepsilon_0 - \frac{B}{8}, \quad (25)$$

$$qa = \pi\left[\frac{2(\varepsilon - \varepsilon_0 + B/8)}{B}\right]^{1/2}. \quad (26)$$

In this case, the expressions for the field fraction in the cladding (21) and estimates of radiation losses (22) take the form

$$A = \frac{1}{8\pi}\left[\frac{B}{2(\varepsilon - \varepsilon_0)}\right]^{1/2}, \quad (27)$$

$$\operatorname{Im}\delta v \approx \frac{B\exp\left[-\pi BN/(\varepsilon - v^2)\right]}{1 + Bqa/(\varepsilon_0 - v^2)} \approx \frac{B^{3/2}\exp\left[-\pi BN/(\varepsilon - \varepsilon_0)\right]}{8\pi\left[2(\varepsilon - \varepsilon_0)\right]^{1/2}}. \quad (28)$$

Expressions (27) and (28) determine the field energy fraction in the cladding and radiation losses, respectively, for the optimal design of a single-mode waveguide.

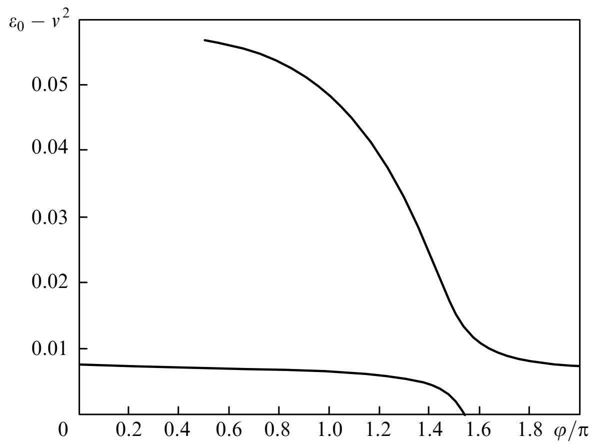

Figure 2. Dependence of the quantity $\varepsilon_0 - v^2$ on the phase φ.

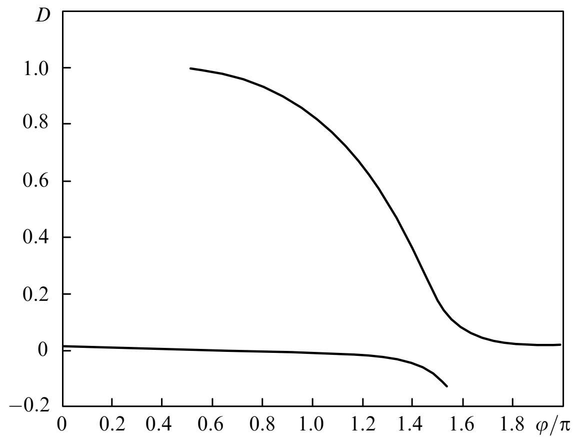

Figure 3. Dependence of the detuning D on the phase φ.

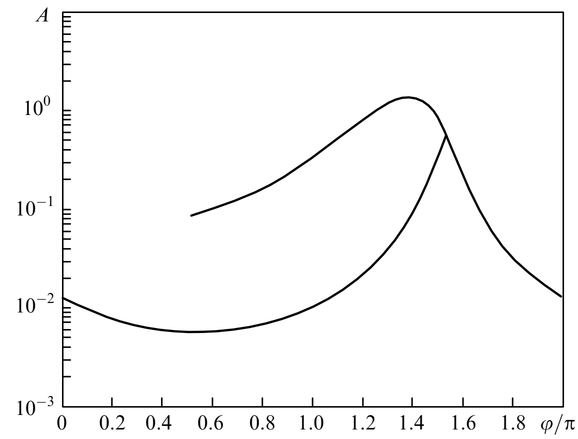

Figure 4. Dependence of the field energy fraction in the cladding A on the phase φ.

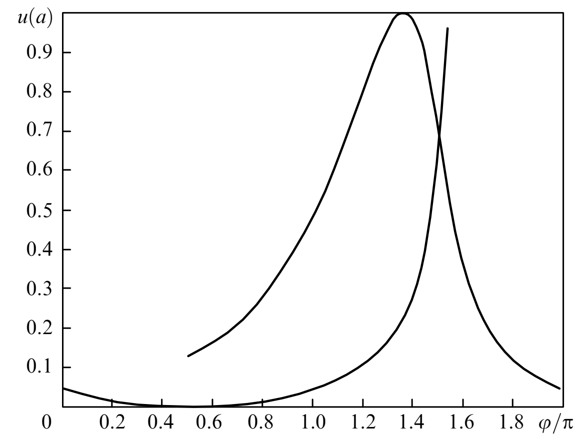

Figure 5. Dependence of the field value at the core–cladding interface $u(a)$ on the phase φ.

4. Dependence of the mode properties on the structure of the waveguide cladding internal boundary

The cladding of a Bragg waveguide is a periodic grating of the refractive index. This raises the natural question: To what degree do the waveguide properties depend on the phase of this grating? Expressions (10), (13), (16), (17)

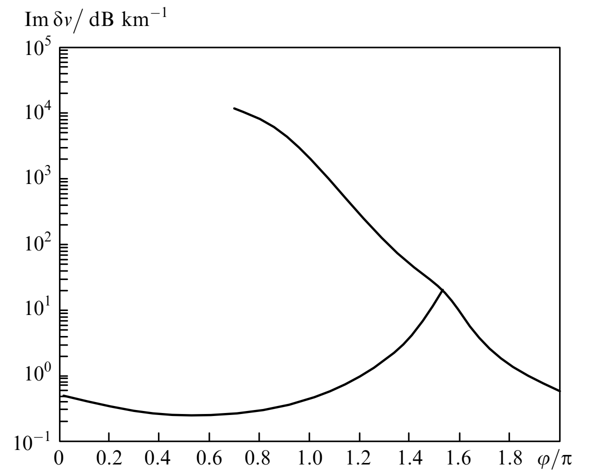

Figure 6. Dependence of radiation losses $\mathrm{Im}\,\delta\nu$ on the phase φ; the number of layers is $N = 150$, $\varepsilon_1 = 2.6$, $\varepsilon = 2.56$, and $B = 0.05$.

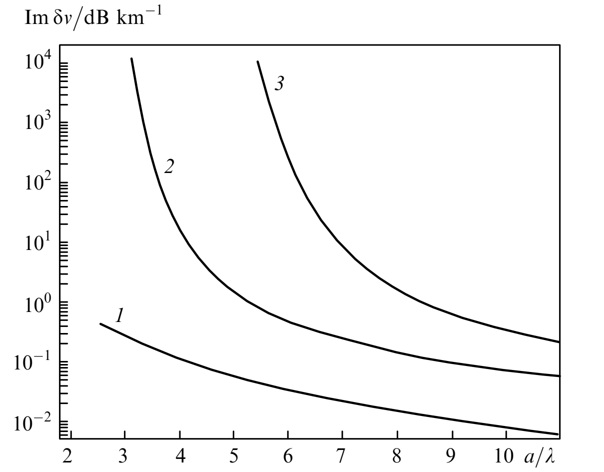

Figure 7. Dependence of radiation losses $\mathrm{Im}\,\delta\nu$ on the core radius a normalised to the wavelength; (*1*, *2*, *3*) are the mode numbers. Parameters are as in Fig. 6.

describing the physical characteristics of the waveguide modes (the field decay rate into the cladding, radiation losses, the field at the boundary, and the field energy fraction in the cladding) allow one to answer this question because they contain the phase dependence φ.

Consider a waveguide with the structure period and the core radius selected so that for $\varphi = \pi/2$ the first mode is central and the second mode is near the excitation threshold [see section 3, expressions (24) and (26)]. Now, by fixing the structure period and the radius of the waveguide core, we will study the dependence of mode properties on the phase φ.

Each mode can be characterised by the effective refractive index ν or by the detuning from the centre of the Bragg reflection band D [see (10)]. The dependences of these quantities on the phase φ are depicted in Figs 2 and 3 (all calculations in Figs 2–7 were performed for $\lambda = 1.55$ μm). One can see that the waveguide at different phases φ can be both single-mode and two-mode one. One can also see that the mode is restricted from one side by the condition $\nu^2 = \varepsilon_0$ and from the other side – by the condition $D = 1$. Figures 4–6 show the dependences of different mode properties on the phase. One can see that these mode properties strongly change with changing the phase.

As expected, the zero field at the core–cladding interface, the minimum of the field energy fraction in the cladding and the minimum of the radiation losses are achieved for the same values of the phase $\varphi = \pi/2$ of the refractive index grating in the cladding.

5. Loss discrimination of modes

In section 4 we considered the waveguide with the core radius and structure period selected so that for $\varphi = \pi/2$ the first mode was central and the second mode was near the excitation threshold. One can see from Fig. 6 that the loss ratio for the first and second modes near this threshold is $\sim 10^{-4}$. It is obvious that, as the core radius a is increased, the losses for the first mode will decrease and the loss ratio for the first and second modes will increase. Nevertheless, this ratio remains much less than unity in some interval of radii, thereby providing the loss discrimination of modes, as demonstrated in Fig. 7. One can see that near the excitation threshold of the third mode ($a/\lambda = 5.5$), the loss ratio for the first and second modes is 0.07. Such a waveguide can be treated as a single-mode one or a quasi-single-mode one for many applications.

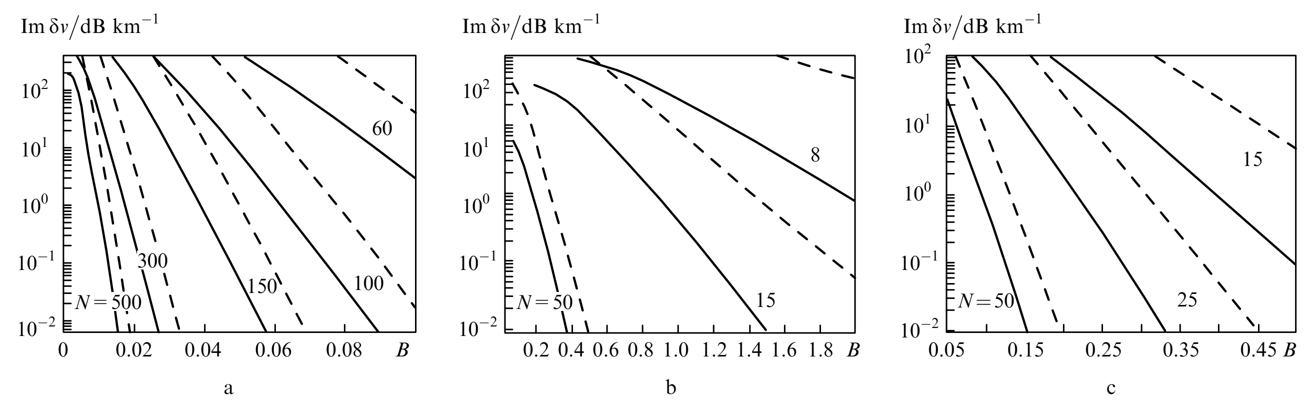

Figure 8. Dependence of the radiation losses on the modulation depth of the refractive index for the first (solid curve) and second (dashed curve) modes on the threshold of the third mode appearance for different numbers N of structure periods and for wavelengths $\lambda = 1.55$ (a), 10.6 (b), 0.245 μm (c); $\varepsilon_1 = 2.6$, and $\varepsilon = 2.56$.

6. Dependence of radiation losses on modulation and number of refractive-index layers in the cladding

It has been shown in section 4 that the waveguide properties significantly depend on the phase, and minimum radiation losses are achieved for $\varphi = \pi/2$. In practice, the minimum level of radiation losses in a Bragg waveguide is determined by the maximum number of layers (periods N) allowable by the modern technology. Naturally, the minimum required number of layers is related to the refractive index modulation δn (or B). The expressions obtained in section 2 can be used to obtain radiation losses almost in all interesting cases. Figure 8 presents quasi-single-mode waveguide losses calculated by (13), (15) for the wavelengths $\lambda = 1.55$, 10.6 and 0.245 μm as a function of the number of layers and the modulation depth of the refractive index.

One can see from Fig. 8 that the hollow-core Bragg waveguide has losses which are three times lower than the value 0.15 dB km^{-1} achieved at present in the optical communication for $\delta n \approx B \approx 0.05$ and the number of periods $N = 150$. For radiation of a CO_2 laser and excimer lasers, losses less than 0.5 dB m^{-1} are of practical interest. One can see from Fig. 8 that in the case of the CO_2 laser radiation, hollow Bragg waveguides have losses of this order for $\delta n \approx \pi B/(2n) \approx 0.6$ and the number of periods $N = 15$. Therefore, for the excimer radiation in Fig. 8, these losses are achieved for the modulation $\delta n \approx B \approx 0.25$ and the number of periods $N = 25$.

However, one should bear in mind that even for $N = \infty$ the hollow-core Bragg waveguide has losses caused by the fundamental absorption of the field. As shown in [6], they limit the losses at the level $\sim 10^{-3}$ dB km^{-1} at 1.55 μm.

7. Conclusions

We have obtained the explicit dependences of the optical properties of a Bragg waveguide on its geometrical parameters. In particular, radiation losses, the ratio of the mode field energy in the core and the cladding, the field at the core–cladding interface and the field decay rate into the cladding have been considered. The relation of the optical properties with the internal boundary structure of the Bragg cladding has been established for the first time. It has been shown that the first layer of the optimal structure has the maximum refractive index and its thickness is equal to half the structure period.

Radiation losses of Bragg waveguides have been considered as an example for radiation at 1.55, 10.6 and 0.245 μm for different modulation depths of the refractive index and different numbers of cladding layers.

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