LASER CAVITIES AND BRAGG GRATINGS DOI: 10.1070/QEL15913

Numerical modelling of a fibre reflection filter based on a metal–dielectric diffraction structure with an increased optical damage threshold

V.S. Terentyev, V.A. Simonov

Abstract. **Numerical modelling demonstrates the possibility of fabricating an all-fibre multibeam two-mirror reflection interferometer based on a metal–dielectric diffraction structure in its front mirror. The calculations were performed using eigenmodes of a double-clad single-mode fibre. The calculation results indicate that, using a metallic layer in the structure of the front mirror of such an interferometer and a diffraction effect, one can reduce the Ohmic loss by a factor of several tens in comparison with a continuous thin metallic film.**

Keywords: *fibre reflection interferometer, diffraction, single-mode fibre, eigenmodes, frequency selection in lasers.*

1. Introduction

Mode selection in laser cavities implies the use of optical components that ensure loss discrimination of modes, thus allowing for single-frequency oscillation, which is of great importance in many areas of science, e.g. in spectroscopic studies or photosensor scanners [1, 2]. This paper presents a theoretical study of a two-mirror multibeam all-fibre reflection interferometer (FRI) [3, 4], which is similar to a fibre-optic Fabry–Perot interferometer (FOFPI) but has other characteristics of its mirrors (Fig. 1). The front mirror (M1) of the FRI contains an absorbing or scattering element and is an asymmetric reflector (with different reflectances on its opposite faces). The rear mirror (M2) should have the highest possible reflectance. It seems likely that the FRI can currently be viewed as the most versatile tool that allows one to obtain narrow-band (~100 kHz) single-frequency oscillation in linear-cavity lasers, together with rapid (~1 kHz) wavelength tuning over a wide spectral range (~100 nm). Such properties are ensured, first, by the fact that the FRI uses reflected light, i.e. it has the same 'non-inverted' profile of interference fringes in reflection as an FOFPI in transmission. Second, if an FRI is used as one of the mirrors of a laser cavity [5], the cavity length can be reduced to the extent that the cavity will support only one oscillation mode, selected according to the loss level. FOFPI-based ring selection schemes include a rather long cavity, which simultaneously supports several modes. Linear schemes utilising fibre Bragg gratings and/or distributed feedback lasers are capable of selecting one mode, but characteristically they have a narrow wavelength tuning range in comparison with the FRI at a high scanning rate of a piezoceramic transducer or have a slow tuning rate in the case of mechanical stretching (compression) [6]. Optical systems that use reflected light and have more than two mirrors, e.g. a Fox–Smith interferometer [7], have a more complex design and are more difficult to fabricate.

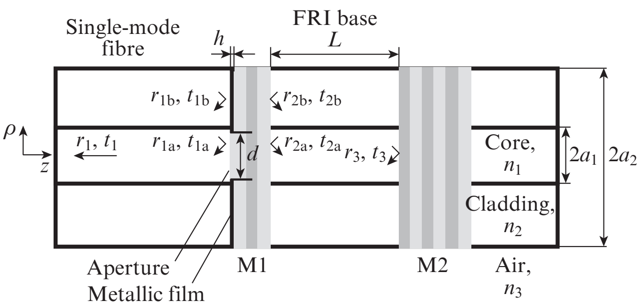

Figure 1. Schematic of the FRI:
(M1) front mirror; (M2) rear mirror; (n_1, n_2, n_3) refractive indices of the core, cladding and air, respectively; see Section 2 for the other parameters.

When an absorbing structure (thin metallic film of thickness $h \approx \lambda/20$) is used, FRIs are rather easy to fabricate, as was demonstrated experimentally by the example of an FRI on a fibre end face [8]. In this configuration of a pseudo-all-fibre reflection interferometer (the interferometer base had no single-mode guiding core), the structure of the front mirror included a continuous metallic film. The optical damage threshold of such a structure in a single-mode fibre is very low. At an incident power of 10–100 μW, the high light intensity and Ohmic absorption lead to strong heating of the film, and the mirror may degrade. It is possible to make an all-diffractive FRI [9], which obviates the problem of the optical damage threshold of its components, but is technologically difficult to implement since, at present, components of an interferometer cannot be produced directly in a waveguide without disturbing its integrity, because use is then made of either a metallic film or a diffraction microstructure and dielectric layers for mirrors. At this point in time, in fabricating components of an FRI the end face of an input fibre can be butted against an interferometer mirror on the end face of a fibre cavity with an optical cement in a ferrule channel. There is also pulsed fusion splicing, which allows one to join two fibres, but the process may damage the mirror. These methods can be applied, in particular, to active fibres. The main criterion for fibre selection is then that they have identical fundamental-mode diameters.

V.S. Terentyev, V.A. Simonov Institute of Automation and Electrometry, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Koptyuga 1, 630090 Novosibirsk, Russia;
e-mail: terentyev@iae.nsk.su, simonovva@iae.sbras.ru

Received 29 July 2015; revision received 23 September 2015
Kvantovaya Elektronika **46** (2) 142–146 (2016)
Translated by O.M. Tsarev

The purpose of this study is to demonstrate the possibility of using diffraction of light by a metallic film with a hole for raising the optical damage threshold of the front mirror of an FRI in comparison with the case of Ohmic absorption in a continuous metallic film. The present results make it possible to create an all-fibre reflection interferometer with reflected-light characteristics (fringe fineness, interference pattern contrast, near-unity reflectance) comparable to those of a FOFPI, which uses transmitted light.

2. Theory

One fundamental distinction of the optical scheme of a single-mode fibre-based FRI (Fig. 1) from that of a three-dimensional prototype [3, 4] is the presence of a guiding core, which suppresses all fundamental transverse modes except for the fundamental one. The front mirror of the FRI has a complex structure: it includes a thin metallic film with a hole of diameter d and a multilayer dielectric coating, which in general may consist of non-quarter-wave layers. As a result, its opposite faces have different reflectances for the fundamental mode. In the case of normal incidence of a travelling light wave of the fundamental mode on the mirror, we can introduce Fresnel amplitude reflection coefficients of the mirror surface with no metallic film, $r_{1a} = \sqrt{R_{1a}}\exp(i\Psi_{1a})$, and the metal-coated surface, $r_{1b} = \sqrt{R_{1b}}\exp(i\Psi_{1b})$. Similarly, if light is incident on this mirror from the cavity, we have $r_{2a,2b} = \sqrt{R_{2a,2b}}\exp(i\Psi_{2a,2b})$. Here, mirror M1 is assumed to have identical transmittances in both directions, i.e. $t_{1a,1b} = t_{2a,2b} = \sqrt{T_{1a,2a,1b,2b}}\exp(i\Phi_{1a,2a,1b,2b})$, which is typical of conventional mirrors. In the above relations, we use reflectance R_{pq} and transmittance T_{pq}, with the respective phases Ψ_{pq} and Φ_{pq} ($p = 1, 2$; $q =$ a, b). Since adjacent zones are assumed to differ in reflection coefficients, i.e. $r_{1a,2a} \neq r_{1b,2b}$, the structure under consideration will scatter (diffract) both reflected and transmitted light. Only the optical energy in the fundamental mode of the fibre far away from the interferometer is of interest here. The reflection and transmission coefficients for this mode differ from those of regions near the surface of mirror M1. Let $r_{1,2} = \sqrt{R_{1,2}}\exp(i\Psi_{1,2})$ and $t_1 = t_2 = \sqrt{T_{1,2}}\exp(i\Phi_{1,2})$ (here $R_{1,2}$ are reflectances with reflection phases $\Psi_{1,2}$, and $T_{1,2}$ are transmittances with transmission phases $\Phi_{1,2}$). Clearly, these coefficients depend on parameters of adjacent regions: $r_{1,2} = r_{1,2}(r_{1a,2a}, r_{1b,2b}, d)$, $t_1 = t_1(t_{1a}, t_{1b}, d)$. The rear, highly reflective mirror of the cavity, M2, has reflection and transmission coefficients $r_3 = \sqrt{R_3}\exp(i\Psi_3)$ and $t_3 = \sqrt{T_3}\exp(i\Phi_3)$ ($R_3 \approx 1$). The FRI base, of length L, consists of the same fibre as the external fibre. The reflectance and transmittance of the interferometer are given by

$$T = \frac{T_1 T_2}{1 + R_2 R_3 - 2\sqrt{R_2 R_3}\cos(2\psi)},$$

$$R = R_1 + \frac{-2R_3 T_1\sqrt{R_1 R_2}\cos\vartheta + 2T_1\sqrt{R_1 R_3}\cos(\vartheta + 2\psi)}{1 + R_3 R_2 - 2\cos(2\psi)\sqrt{R_3 R_2}} + \frac{R_3 T_1^2}{1 + R_3 R_2 - 2\cos(2\psi)\sqrt{R_3 R_2}}, \quad (1)$$

$$\psi = \frac{2\pi L}{\lambda} - \frac{\Psi_3 + \Psi_2}{2}, \quad \vartheta = \Psi_1 + \Psi_2 - 2\Phi_1.$$

As seen from (1), the expression for R is more complex than that for T: it comprises three terms, which represent two-beam interference of the light reflected from mirror M1 with the light leaving the interferometer. The first two terms are zero or tend to zero as R_1 approaches zero. Only the third term is then essential, and the expression for $R(\psi)$ coincides with that for $T(\psi)$ to within a constant factor. If $R_1 \neq 0$ and $\vartheta \neq (2m + 1)\pi$ (where m is an integer), which is characteristic of systems with losses, the $R(\psi)$ profile is asymmetric. In the limit of $R_3 = 1$ and $R_1 = 0$, we have

$$T = 0, \quad R = \frac{T_1^2}{1 + R_2 - 2\cos(2\psi)\sqrt{R_2}}. \quad (2)$$

Since mirror M1 may cause considerable Ohmic or diffraction losses for a travelling light wave on its side coated with a metallic film, the sum of its reflectance and transmittance may differ considerably from unity. Note that mirrors having identical reflectances may have different transmittances (including zero transmittance) due to different losses. For the maximum value of R to be close to unity, transmittance T_1 should have a certain value, satisfying the law of conservation of energy. A theoretical study [10] demonstrates that the system under consideration, with diffraction losses, has $T_1 = (1 - R_2)/2$ and a maximum reflectance $R_{max} = (1 + \sqrt{R_2})^2/4$. In contrast to the theoretically possible maximum transmittance of an FOFPI, which is unity, the maximum reflectance of an FRI is always less than unity, but, if R_2 is close to unity, R_{max} also approaches unity.

To evaluate reflection and transmission coefficients for a travelling wave, use can be made of the theory of optical fibre eigenmodes [11]. For this purpose, it is sufficient to consider a simple system comprising only a guiding core and a cladding of infinite radius. However, to demonstrate the effect of scattering by this structure, one should find the continuous mode spectrum of scattered light, which is a rather nontrivial problem [12]. It is, therefore, more illustrative to consider a double-clad system comprising a single-mode fibre (which consists of a guiding core and a cladding of finite radius) and an infinite external medium (air), which best represents reality [9]. Then, if the radius of the cladding is large enough that its normalised frequency parameter $V_2 = 2\pi a_2(\lambda\sqrt{n_2^2 - n_3^2})^{-1}$ (Fig. 1) far exceeds 2.4, the cladding has a large number of eigenmodes (cladding modes), which may account for a considerable part of the optical energy.

Let an FRI have a response function similar to the R profile in (2) and the metallic film have no hole ($d = 0$). The film should then be ~10–20 nm thick, and its Ohmic absorption in a free-standing state for a travelling light wave will then be ~30%. Incorporating such a film into the mirror structure markedly increases the absorption in the film, resulting in a low optical damage threshold of the entire structure [3]. The Ohmic loss in the film can be reduced by increasing its thickness and utilising highly reflective metals. For example, thicker films ($h > 30$ nm) have near-zero transmission, and highly reflective metals, such as Au, Ag and Al, have considerably higher reflectance. As a result, the Ohmic loss drops by a factor of several tens.

In the case of an asymmetric mirror based on a thin metallic film with $R_1 = 0$, changing the film thickness will reduce the difference between the reflectances for light incident on the two surfaces of the mirror, i.e. the matching condition will be violated and the difference between the reflectances will decrease ($R_1 \rightarrow R_2$). Therefore, this is unreasonable for a continuous film. At the same time, if the Ohmic loss is redistributed in favour of the scattering (diffraction) loss by increasing the thickness of the metal, the asymmetry of the reflectances ($R_1 \to 0$, $R_2 \to 1$) can be maintained. This is possible, first, because from the viewpoint of Eqns (1) the nature of the loss is of no importance. Second, the phase shift acquired by light reflected from metals differs from that in the case of a quarter-wave multilayer dielectric coating. Thus, two adjacent highly reflective regions producing different phase shifts of reflected waves cause far-field diffraction, like in the case of a diffraction grating. In the case of a diffraction-based three-dimensional FRI [10], these regions should have identical areas and reflectances, and the phase shift between reflected waves ($\Psi_{1a} - \Psi_{1b}$) should be π. An interferometer with such a front mirror may have a response function in reflection of the form (2). Calculations are then made in the plane wave approximation.

In the interferometer schematised in Fig. 1, the optical field incident on the front mirror has a nonuniform amplitude, so the hole diameter at which $R_1 = 0$ should be found numerically. The reflection and transmission coefficients of mirror M1 can be evaluated by expanding the optical field in terms of the eigenmodes of the fibre:

$$t_{im} = \frac{1}{2}\int_0^{2\pi}\int_0^{\infty}(t_{i\rho}\boldsymbol{E}_{11}\times\boldsymbol{H}^*_{1m})_z\rho\mathrm{d}\rho\mathrm{d}\varphi,$$

$$r_{im} = \frac{1}{2}\int_0^{2\pi}\int_0^{\infty}(r_{i\rho}\boldsymbol{E}_{11}\times\boldsymbol{H}^*_{1m})_z\rho\mathrm{d}\rho\mathrm{d}\varphi,$$

$$r_{i\rho} = \begin{cases} r_{ia}, \rho \leqslant a_1 \\ r_{ib}, \rho > a_1 \end{cases}, \quad t_{i\rho} = \begin{cases} t_{ia}, \rho \leqslant a_1 \\ t_{ib}, \rho > a_1 \end{cases}, \tag{3}$$

$$\frac{1}{2}\int_0^{2\pi}\int_0^{\infty}(\boldsymbol{E}_{\nu n}\times\boldsymbol{H}^*_{\mu m})_z\rho\mathrm{d}\rho\mathrm{d}\varphi = \delta_{\nu\mu}\delta_{nm},$$

where $i = 1$ or 2; the overlap integrals are calculated in terms of the Poynting vector [13]; $\boldsymbol{E}_{\nu n}$ and $\boldsymbol{H}_{\mu m}$ are the electric and magnetic field vectors, respectively; ν and μ are the angular mode numbers; n and m are the radial mode numbers; $r_{i\rho}$ and $t_{i\rho}$ are the radial distributions of the reflection and transmission coefficients; and the subscript z in the integrands denotes the z components of the cross products. The angular mode number is taken to be unity because of the axial symmetry in the geometry of the optical system under consideration, and modes with other angular numbers are not excited, i.e. their overlap integrals with respect to angle φ are zero because of their different angular numbers, since $r_{i\rho}$ and $t_{i\rho}$ are angle-independent. It follows from (3) that $R_i \equiv R_{i1} = |r_{i1}|^2$ and $T_i \equiv T_{i1} = |t_{i1}|^2$ (where $i = 1$ or 2).

3. Calculation

We now turn to numerical modelling of a particular system using characteristics of Corning SMF-28e single-mode fibre [14]. Since real fibre does not fully correspond to the optical scheme chosen, e.g. in that the transition region between its core and cladding is not very sharp, we change one of its parameters – the numerical aperture NA at a wavelength of 1550 nm – so that the 1/e^2 mode field diameter (MFD) becomes 10.4 ± 0.5 μm and the effective refractive index n_{eff} for the fundamental mode becomes 1.4682. The other parameters are then as follows: NA = 0.115, $n_1 = 1.471$, $n_2 = (n_1^2 - \mathrm{NA}^2)^{1/2} = 1.4665$, $n_3 = 1$, MFD = 9.9 μm and $a_1 = 4.1$ μm (Fig. 1). Since the difference $|n_{1,2} - n_{\mathrm{eff}}|$ is small, the angle of incidence of the mode on the front mirror can be taken to be zero.

The mirrors of the FRI differ in structure. Mirror M2 may consist of a large number (~30) of quarter-wave dielectric layers with refractive indices $n_{\mathrm{high}} = 2.35$ (TiO_2) and $n_{\mathrm{low}} = 1.46$ (SiO_2), which ensures very high reflectance, nearly the maximum possible (> 99.9%). The structure of mirror M1 includes a quarter-wave coating with a smaller number of layers to ensure that its reflectance is lower than that of mirror M2 and that the reflectance of the interferometer is near unity. Let the input face of mirror M1 be covered with an aluminium film of thickness h = 30 nm. Given that the refractive index of aluminium, n_{Al}, at a wavelength of 1550 nm is 1.51 – 15.23i [15], at this film thickness and identical refractive indices n_1 of the media in contact with the film we obtain a reflectance $R_{\mathrm{Al}} = 0.95$, transmittance $T_{\mathrm{Al}} = 0.00356$ and Ohmic absorption $A_{\mathrm{Al}}^{\mathrm{ohm}} = 1 - R_{\mathrm{Al}} - T_{\mathrm{Al}} = 0.0445$. At larger aluminium layer thicknesses, the loss $A_{\mathrm{Al}}^{\mathrm{ohm}}$ varies only slightly, primarily because of the decrease in transmittance, so thicker layers can be used as well. The number of quarter-wave dielectric layers is taken to be eight (four SiO_2 and four TiO_2 layers) to illustrate the case of a high-finesse cavity.

The Ohmic and diffraction losses in mirror M1 were evaluated as

$$A_{1,2}^{\mathrm{ohm}} = \frac{1}{2}\int_0^{2\pi}\int_0^{\infty}(\boldsymbol{E}_{11}\times\boldsymbol{H}^*_{11})_z(1 - |r_{1\rho,2\rho}|^2 - |t_{1\rho}|^2)\rho\mathrm{d}\rho\mathrm{d}\varphi, \tag{4}$$

$$A_{1,2}^{\mathrm{dif}} = A_{1,2} - A_{1,2}^{\mathrm{ohm}},$$

which corresponds to the area-integrated Ohmic loss when a normally incident light wave passes through the metallic film with a hole. The diffraction loss was determined using the law of conservation of energy: by subtracting the Ohmic loss from the total one. The total loss was evaluated as $A_{1,2} = 1 - R_{1,2} - T_{1,2}$. Using relations (3) and (4), we plotted the reflectances, transmittance and absorptances of mirror M1 against the diameter d of the hole in the aluminium film (Fig. 2). At $d = 0$, the transmittance of mirror M1 is essentially zero, in particular owing to the presence of the highly reflective dielectric coating. With increasing hole diameter, R_1 strongly decreases, down to 0.006, as a result of diffraction. At the same time, reflectance R_2 decreases only slightly (to 0.957, which is close to the reflectance of the multilayer dielectric coating), and transmittance T_1 increases to 0.021. The hole diameter corresponding to the minimum in reflectance is $d_{\mathrm{min}} = 0.735 \cdot 2a_1$. Figures 2b and 2c show Ohmic and diffraction losses as functions of d for mirror M1. At $d = 0$, the total absorptances are equal to the Ohmic ones: $A_{1,2} = A_{1,2}^{\mathrm{ohm}}$. With increasing d, the Ohmic absorptances decrease because of the decrease in the fraction of optical energy passing through the film, but the total absorptances increase, together with the increase in diffraction loss. At $d = d_{\mathrm{min}}$, we have $A_1 = 0.972$, $A_1^{\mathrm{ohm}} = 0.023$, $A_1^{\mathrm{dif}} = 0.95$, $A_2 = 0.022$, $A_2^{\mathrm{ohm}} = 0.0005$ and $A_2^{\mathrm{dif}} = 0.0215$. The ratio of the diffraction loss to the absorption loss is $A_1^{\mathrm{dif}}/A_1^{\mathrm{ohm}} = 41.1$. In an FRI based on a continuous film, at the minimum reflectance of the interferometer essentially all incident energy should be absorbed in the film as a result of Ohmic losses [3]. In the case under consideration (at $d = d_{\mathrm{min}}$), a factor of 43.4 less energy will be absorbed, which means an increase in the optical damage threshold of mirror M1.

The effect of incident light scattering can be illustrated by the example of taking into account cladding modes. Figure 3

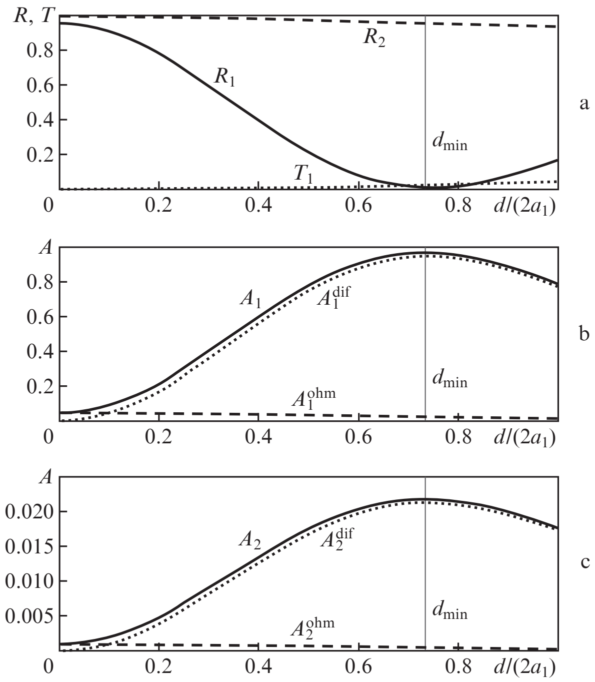

Figure 2. Reflectances $R_{1,2}$, transmittance T_1 and absorptances $A_{1,2} = A_{1,2}^{\rm ohm} + A_{1,2}^{\rm dif}$ of mirror M1 as functions of the diameter d of the hole in the metallic film.

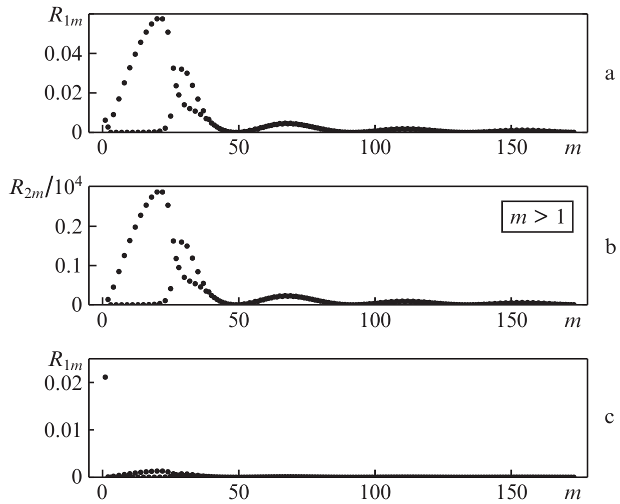

Figure 3. Reflectances $R_{1m,2m}$ and transmittance T_{1m} of mirror M1 for all cladding modes. The angular mode number is unity.

shows reflectance and transmittance distributions over all cladding modes. The sum energies in the higher order modes (without the fundamental mode) are $\sum_{m=2}^{N} R_{1m} = 0.869$, $\sum_{m=2}^{N} R_{2m} = 4.34\times10^{-4}$ and $\sum_{m=2}^{N} T_{1m} = 0.021$. Since $\sum_{m=2}^{N} R_{1m} < A_1^{\rm dif}$, some of the scattered energy (0.081) passes into radiation modes, which are left out of consideration in the calculation method used.

Figure 4 presents the reflectances and transmittance of the front mirror in the range 1500–1600 nm, calculated under the assumption that the materials of the mirror have no dispersion in this spectral range. The parameters vary only slightly and, according to Eqn (1), this causes no marked distortion of the interferometer response function $R(\psi)$. This

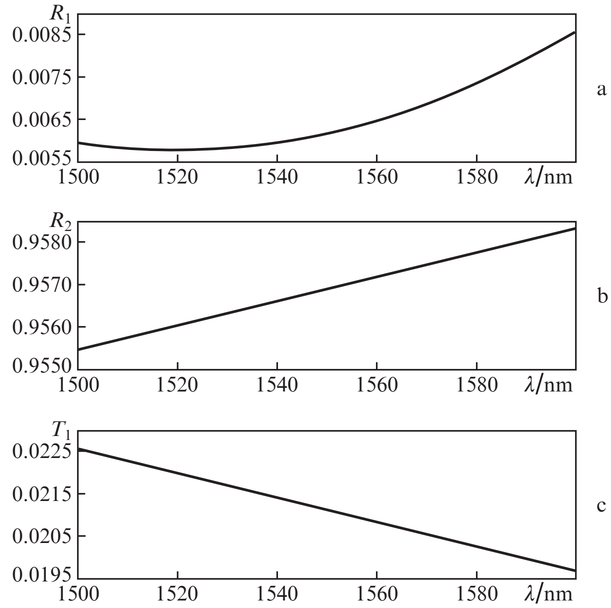

Figure 4. Spectral dependences of the reflectances and transmittance of mirror M1 for the fundamental mode.

means that the main characteristics of the interferometer (fringe fineness, contrast and maximum reflectance in the spectral range in question) undergo no significant changes and it is suitable for use as a mode discriminator in fibre lasers.

4. Conclusions

We have performed numerical modelling of a fibre reflection interferometer. Calculation results indicate that an aluminium coating with a hole increases the optical damage threshold of the front mirror of the interferometer by 43 times in comparison with a continuous film. This offers the possibility of using such an interferometer as a frequency filter in single-mode fibre-based laser cavities. The calculations were made using the theory of eigenmodes of a double-clad single-mode fibre. The reflection interferometer considered in this study can be used as a frequency filter in short-linear-cavity lasers with a configuration proposed previously [5] and in cavities of single-mode laser diodes based on single-mode fibre with an output power on the order of 1 mW. Since the Ohmic loss depends directly on the properties of a thick ($h > 30$ nm) metal layer, it is obvious that, using higher reflectance metals, one can further reduce the Ohmic loss in the structure of the front mirror.

Acknowledgements. This work was supported by the Russian Science Foundation (Grant No. 14-22-00118).

References

1. Lee B.G., Belkin M.A., Audet R., MacArthur J., Diehl L., Pflügl C., Capasso F., Oakley D.C., Chapman D., Napoleone A., Bour D., Corzine S., Höfler G., Faist J. *Appl. Phys. Lett.*, **91**, 231101 (2007).
2. Buric M., Falk J., Chen K.P. *Opt. Express*, **14** (6), 2178 (2006).
3. Troitskii Yu.V. *Mnogoluchevye interferometry otrazhennogo sveta* (Multibeam Reflected-Light Interferometers) (Novosibirsk: Nauka, 1985).

4. Terent'ev V.S. *Avtometriya*, **45** (6), 89 (2009).
5. Terentyev V.S., Simonov V.A. *Kvantovaya Elektron*., **43** (8), 706 (2013) [*Quantum Electron*., **43** (8), 706 (2013)].
6. Mao Q., Lit J.W.Y. *IEEE J. Quantum Electron.*, **39** (10), 1252 (2003).
7. Barnsley P., Urquhart P., Millar C., Brierley M. *J. Opt. Soc. Am. A*, **5** (8), 1339 (1988).
8. Terentiev V.S., Dostovalov A.V., Simonov V.A. *Laser Phys.*, **23**, 085108 (2013).
9. Terent'ev V.S. *Avtometriya*, **48** (4), 41 (2012).
10. Kol'chenko A.P., Terent'ev V.S., Troshin B.I. *Opt. Spektrosk*., **101** (4), 674 (2006).
11. Dianov E.M., Prokhorov A.M. *Usp. Fiz. Nauk*, **148** (2), 289 (1986).
12. Marcuse D. *Theory of Dielectric Optical Waveguides* (San Diego: Academic Press, 1974).
13. Marcuse D. *Bell Syst. Tech. J.*, **56** (5), 703 (1977).
14. http://www.corning.com/worldwide/en/products/communication-networks/products/fiber/smf-28e--ll.html.
15. Rakić A.D., Djurišic A.B., Elazar J.M., Majewski M.L. *Appl. Opt*., **37**, 5271 (1998).