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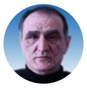

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Waveguide Resonator with High Quality Factor Excited Through the Subwavelength Slit

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Abstract—The excitation of standing TM waves by a subwavelength slit in the single-mode waveguide resonator with the metallic borders is considered. In this structure, the input energy through the slit strongly depends on the incident wavelength. Consequently, the *Q*-factor of the system computed by the finite element method reaches the values of 10^4 in the near infrared region. The significant change of the scattered wave energy is achieved by the changing of dielectric constant value by 5×10^{-4} or the thickness of resonator by 0.5 nm. The sensitivity of system to the parameters of structure allows one to use the system in various applications such as devices of optical bistability, modulators, and optical sensors of vibration, displacement and temperature.

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Keywords: waveguide resonator, *Q*-factor, subwavelength slit, finite element method

1. INTRODUCTION

The progress of the fiber and integrated optics resulted in the development of a wide range of small-sized optical devices, filters, modulators, deflectors, and etc. An essential part of almost any complex optical and microwave device is a resonator [1–4]. One of the key directions of development of today's physics is a quantum theory of measurements and the related interest to manipulations with the individual quantum objects. The optical resonators are the base elements and play a significant role both in these studies [5–6] and in the studies of an optical bistability [7] and the Raman scattering [8]. It is with the use of miniature resonators with high *Q*-factor the nonclassical states of electromagnetic field were first demonstrated in the optical range and were held the impressive experiments on the interaction between individual photons and individual atoms [9–12]. Closely related to this direction are such applications as quantum computers, quantum cryptography and quantum processing of information [5–6, 13]. One of the main requirements to observe the quantum effects is the isolation of the system from the classical outside world and the decrease of the dissipation in it, which means increasing *Q*-factor for the resonator. For practical applications, it is important to have resonators with the high *Q*-factor and small volume *V* of modes, because the ratio Q/V determines the intensity and the time of coherence of various interactions of the cavity and the integrability of device. Currently, among the various microstructures, the most promising are optical Fabry–Perot cavity resonators [14–16], microcylinders [17], microtoroids [18] and photonic crystals [19–20]. In turn, in plasmonic resonators one can obtain a high degree of mode confinement within the subwavelength limits [21–23]. However, the internal losses related to the plasmon–polariton surface modes essentially reduce the *Q*-factor of plasmonic resonators to the values far below their dielectric analogues [24–26].

It should be noted that despite the simplicity of the geometrical design, out of the view of researchers proved the single-mode waveguide resonator with the metal borders (Fig. 1). Apparently, this is due to the problems with the wave energy input to structure and relatively large losses. In the present study, we investigated the possibility to excite the cavity through a subwavelength slit, which creates favorable conditions for increasing the Q-factor of the resonator. In [27], the process of transmission of perpendicularly polarized light through the subwavelength slit milled in the thin screen of a perfect electrical conductor is analytically investigated. These results are consistent with the numerical computations and demonstrate that the slits with the width of about 100 nm may result to nonresonant (broadband) 100-fold enhancement of the field amplitude and ~10 times of the transmission efficiency in the IR spectral region. This fact opens up new opportunities to improve the metal single-mode waveguide cavity resonators.

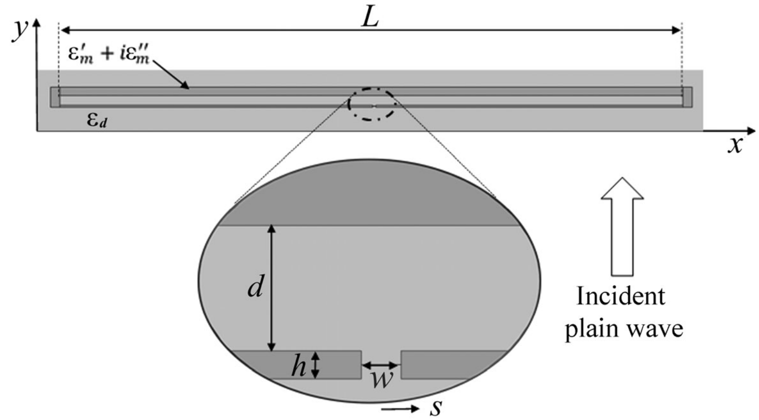

Fig. 1. Scheme of the cross-section of structure. The dark area is filled with the silver, while the rest is filled with a dielectric medium with the permittivity ε_d, where s is a shift of the slit center from the center of the cavity resonator.

The input/output system of wave energy through the slit has the following advantages. Firstly, this eliminates the need to reduce the thickness of the metallic sidewall of the resonator to provide the input/output of the wave energy through it. At wall thicknesses considerably exceeding the skin layer, the penetration of the field into the metal is reduced significantly and, as a result, the losses are diminished. Secondly, the wave, which exits the resonator, has a strong divergence because of the subwavelength width of the slit and it is easily separable from the wave reflected from the wall. Thirdly, changing the position of the slit relative to the distribution of the field of a standing wave in the resonator, it is possible to control the input/output of radiation and, therefore, the Q-factor of the resonator. Fourthly, there is no need of focusing the light beam for optimal excitation of single-mode regime. Below we show that these advantages enable one to increase significantly the Q-factor of the resonator.

2. STRUCTURE OF THE SYSTEM AND THE COMPUTING METHOD

The structure of the plane-parallel resonator with the subwavelength slit is shown in Fig. 1. The considered structure is analyzed with the use of the finite element method (FEM) using the COMSOL Multiphysics software. The numerical computations are realized in two-dimensional 2D model because the fields are identical along the z-axis.

The behavior of waves in the near-IR region at wavelengths λ close to 1000 nm is investigated, because there are good semiconductor lasers in this range and optimal conditions are created to support the plasmonic and vibrational modes simultaneously in the resonator. To have a single-mode waveguide resonator, the following parameters were taken: the width of the cavity d = 316 nm, the length of resonator L = 20000 nm, and the dielectric constant of the surrounding medium ε_d = 2.5. To avoid radiation losses from the surfaces of resonator, the left, right and upper metal layers are made much wider than the lower metal layer. To excite the resonator, the main role is played by the bottom metal layer, which has the slit with the size w. To follow the conditions of an enhancement of the effectiveness of transmission through the slit imposed by the theory described in the [27], the thickness h of the lower metal plate is taken less than the size of the slit w. For the permittivity of silver we used the values of the work [28]. The excitation of the resonator was carried out by a plane wave which had only the component E_x, and was incident on the lower metal surface.

3. RESULTS AND DISCUSSION

The dependences of the wave fields on the wavelength of the incident radiation in the presence of a dielectric medium with the ε_d = 2.5 are investigated. Figure 2 shows the distribution of the component of the wave field E_x.

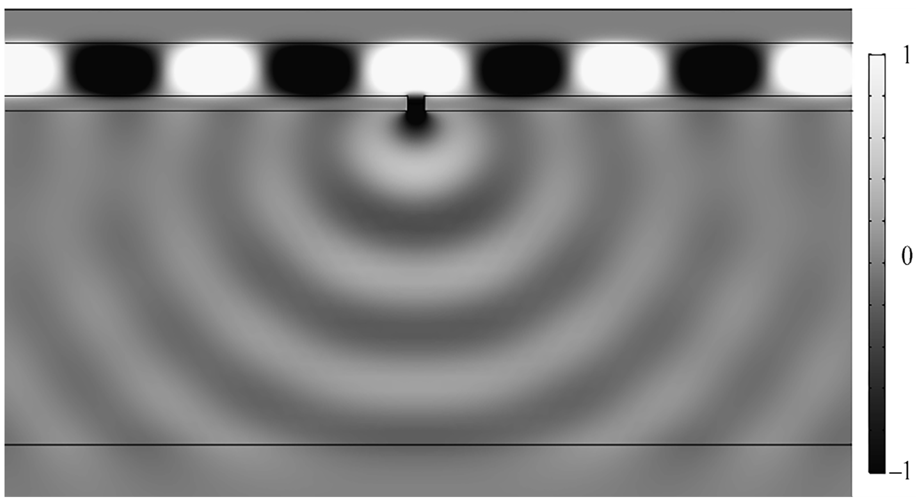

Fig. 2. The field component E_x excited at the resonance wavelength 1008.75 nm by the subwavelength slit in the silver plate of a plane-parallel resonator. The length of resonator is L = 20000 nm, the width d = 316 nm, the slit size w = 100 nm, the thickness of the lower metal layer h = 70 nm, the shift of slit from the center of the resonator s = 0 nm and the permittivity of the medium ε_d = 2.5.

From the ratio of the width of the resonator and the wavelength of the resonator (Fig. 2), as well as from the polarization of the electric field one can easily see that the fundamental oscillatory TM-wave is formed in the resonator, described by the dispersion relation

$$\tan\left(\frac{\chi_d}{2}d\right)=\frac{æ_m}{\chi_d}\frac{\varepsilon_d}{\varepsilon_m}, \tag{1}$$

where

$$\chi_d=\sqrt{\varepsilon_d\frac{\omega^2}{c^2}-k^2}, \tag{2}$$

$$æ_m = \sqrt{k^2 - \varepsilon_m \frac{\omega^2}{c^2}}\,. \tag{3}$$

Here k is the wave number of the TM-wave, ω the angular frequency, and c the speed of light in vacuum.

Figure 3a shows the dependence of an absolute value of E_x in the resonator on the wavelength in vacuum for various thicknesses h of the metallic layer. Here, along with the formation of the waveguide mode at the wavelength of 990 nm, the other modes with the lower values of Q-factor are formed. It can be assumed that these modes are formed by different ways, because the phases of the modes respond oppositely at the influence of the incident wave with the increasing thickness of the metal layer. At the thickness of 50 nm the penetration through the layer is considerable, which contributes to the resonant formation of the mode with the low values of Q-factor. However, this case is unfavorable for the waveguide mode at a wavelength of 990 nm, because both the internal and radiation losses are great. Meanwhile, at a thickness of 90 nm practically, there is no penetration through the metallic layer the only channel that inputs energy to the resonator is the slit. Then, the modes with the low Q-factors in the resonator are weaken and, oppositely, the waveguide mode at the wavelength of 990 nm is amplified sharply. The point is that at the increase in the thickness of the metal layer the value of the electric field in the metal weakens substantially and, as a result, the internal losses of the resonant waveguide mode are also reduced. Thus, in terms of the input of the wave energy into the resonator through the slit, the Q-factor of the resonant mode reaches 10^4, which is impossible to achieve at the penetration of the wave energy through the sidewalls. It should be noted that such a high value of the Q-factor is achieved in the near-IR region using relatively simple structure and excitation method.

Figure 3b represents the dependence of the amplitude E_x in the resonator on the wavelength for different values of the shift of slit s. Obviously, the resonant frequency of the system and the distance between the peaks are changing. Under these conditions, the wave field distribution is very sensitive to

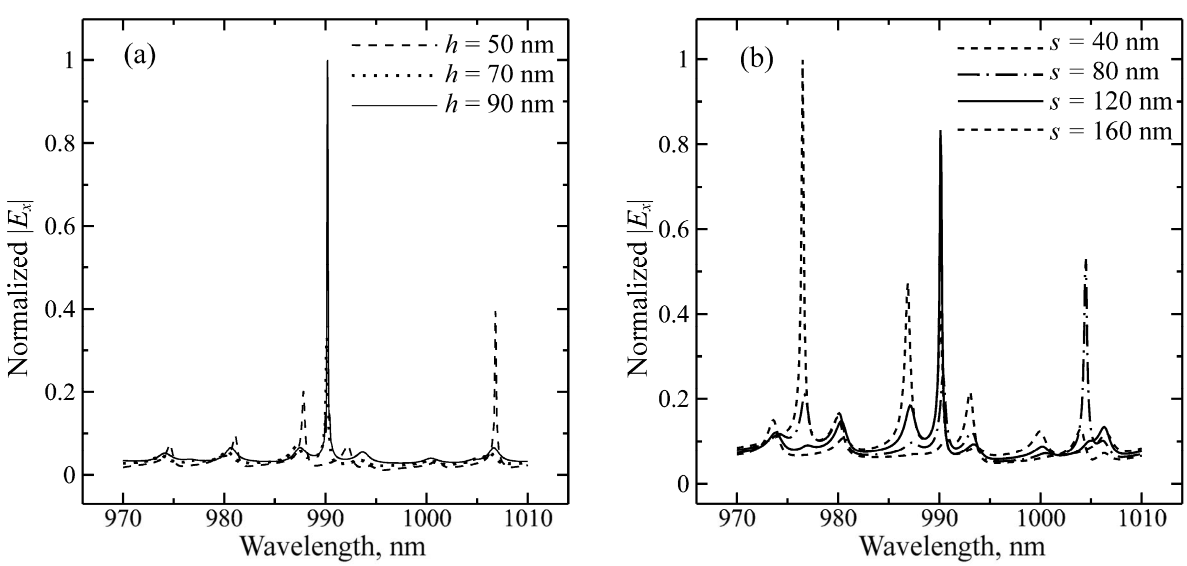

Fig. 3. Dependence of the absolute value of the amplitude E_x in the resonator on the wavelength for (a) the different values of h, when the shift of the slit from the center of resonator s =120 nm, and (b) at the different s, when the height of the lower metal h = 70 nm. The length of the resonator L = 20000 nm, the width d = 316 nm, and the size of the slit w = 100 nm, the permittivity of the medium ε_d = 2.5.

changes in the structure parameters. This makes it possible to control the values of the resonant wavelength and distances between the peaks.

We also investigated the dependence of the field in the resonator on the permittivity of the resonator (Fig. 4a) and the width of the resonator (Fig. 4b). As seen in Fig. 4a, an essential change of the scattered wave energy can be achieved by changing the value of the permittivity by the value of 5×10^{-4}. The same result can be achieved by varying the width of the resonator by 0.5 nm. The sensitivity to parameters of structure enables one to use the system in a variety of applications: in the devices of optical bistability, modulators and optical sensors of vibration, displacement, and temperature.

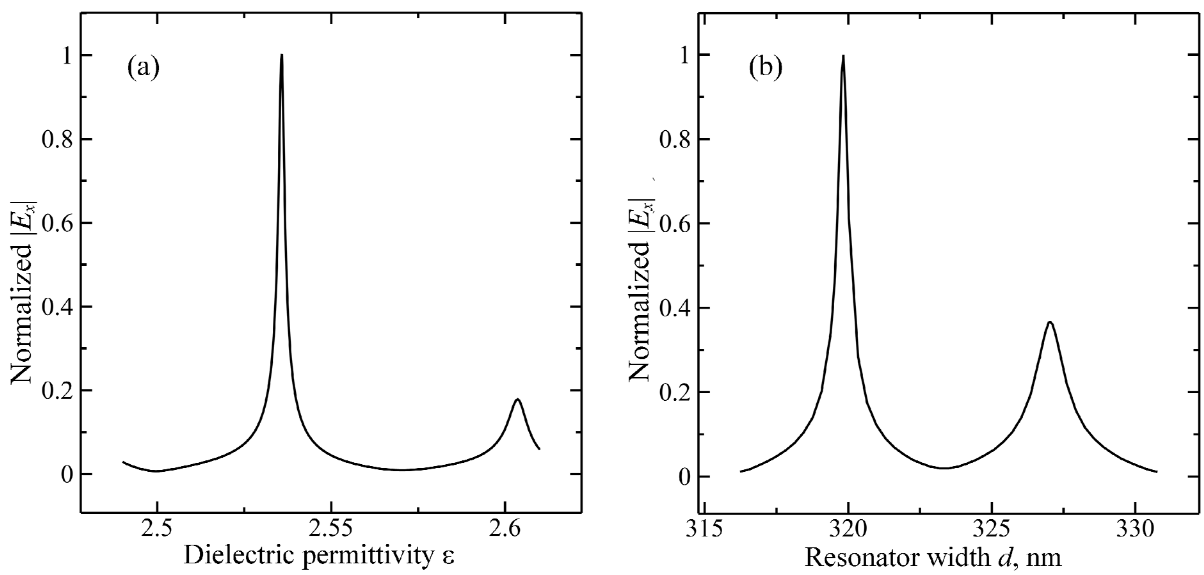

Fig. 4. Dependence of the absolute value of the amplitude E_x in the resonator on (a) the relative dielectric constant of the medium and (b) the width d of the resonator. The resonator length is L = 20000 nm, the width d = 316 nm, the size of the slit w = 100 nm, the height of the lower metal h = 70 nm, the slit shift from the centrum of resonator s = 0 nm, and the wavelength 1000 nm.

Moreover, from Figs. 4a and 4b it follows that the dependences of the wave field inside the resonator on the dielectric constant and on the width of the resonator have almost the same character, that is, the physical basis is the same for these cases. Indeed, a change in permittivity introduces the change in the wavelength in the resonator, and the resonance condition is changing. On the other hand, when we fix the wavelength and modify the width of a resonator, the resonant condition is also changing. Both these scenarios have to satisfy one and the same phase matching condition, that is why a similar resonant peaks have a similar shape.

4. CONCLUSION

The possibility of the excitation of a single-mode waveguide resonator with the metal borders through the subwavelength slit, which creates the favorable conditions to increase the Q-factor is explored. Under these conditions, the phase shift of the transmitted radiation depends essentially on the wavelength of incident wave, which enables one to increase the Q-factor up to 10^4 in the near IR region. The accumulation of the wave field in the resonator is very sensitive to changes of the structure parameters. It is shown that the power, which is scattered out of the structure can be controlled by changing the effective dielectric constant of the medium filling the resonator. For example, altering the dielectric constant by an amount of 5×10^{-4}, one can reach the change of power by more than four times. The same result can be obtained by changing the width of the resonator by 0.5 nm. The investigated properties of the proposed resonator will open the wide range of possible applications of the structure from the devices of optical information processing up to the various sensors.

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