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Comparison between TE and TM modes in superconducting multilayer optical planar waveguides

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The variational method is applied to determine the propagation eigenmodes in a waveguide where a lossless glass substrate has refractive index lower than that of the lossy superconducting guiding layers. For this waveguide, the TM mode is more confined within the core layer and in superconducting thin films and more evanescent in the air claddings in comparison with the TE mode. The maximum for the imaginary part of the effective index and the maximum of the fractional power guided in superconducting layers for TM mode are smaller and shifted to higher values of the glass thickness in comparison with the TE mode.

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1. Introduction

The knowledge of optical propagation characteristics such as the propagation constant and the power distribution among the different layers of the superconducting multilayer optical waveguides is very important for the design of a new class of ultrasensitive, ultrafast and ultralow-noise detectors which are based on sensitive superconductive materials in an optical waveguide configuration [1]. The key phenomenon for the detection of light for frequencies above the gap frequency of superconductors is to annihilate Cooper pairs and create two times as many normal electrons as the broken Cooper pairs [1].

In this paper, we apply a variational method [2, 3] and extend the study from Ref.[1] by considering the TM modes in a waveguide where a lossless glass substrate has refractive index lower than that of the lossy superconducting guiding layers (see the inset from Fig. 1).

2. Superconductor planar waveguide

In our analysis, the planar waveguide structure is obtained by growing two YBCO thin films on a glass substrate which is located in the air. The scalar-wave equation for a slab waveguide is given by

$$\frac{d^2\psi(x)}{dx^2} + k^2 n^2(x)\psi(x) = \beta^2\psi(x), \qquad (1)$$

where β is the propagation constant, k is the free space wave number, $n(x)$ is the refractive index profile

$$n(x) = \begin{cases} n_s, & for \quad x < d_1 = 0, \\ n_i, & for \quad d_i < x < d_{i+1}, i = 1,2,3, \\ n_c, & for \quad d_4 < x, \end{cases} \qquad (2)$$

n_s, n_1, n_2, n_3, and n_c are the refractive index of the air, YBCO film, glass core, YBCO film and air cladding, respectively. The effective index β/k for the TE and TM modes can be found from the dispersion equation which is obtained by applying the boundary conditions at the interfaces between different layers.

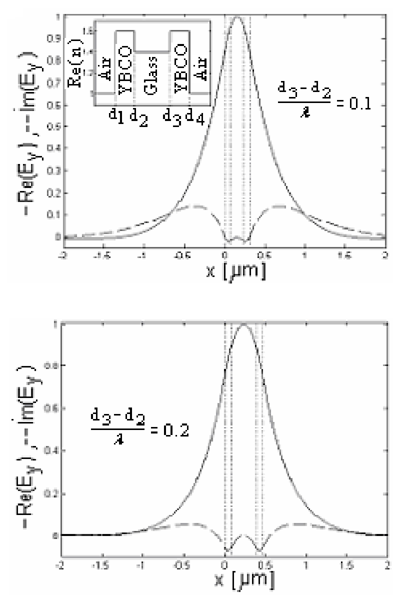

Fig. 1. The real part and imaginary parts of the fundamenta l field profile E_y, for a waveguide with d_1 = 0μm, d_2 = 0.08μm, d_3 = 0.235μm, d_4 = 0.315μm, d / λ = 0.1, n_s = 1, n_1 = $\sqrt{2.32-1.536j}$, n_2 = $\sqrt{2.07}$, n_3 = $\sqrt{2.32-1.536j}$, n_c = 1, λ = 1.55μm and for a waveguide with d_1 = 0μm, d_2 = 0.08μm, d_3 = 0.235μm, d_4 = 0.315μm, d / λ = 0.2, n_s = 1, n_1 = $\sqrt{2.32-1.536j}$, n_2 = $\sqrt{2.07}$, n_3 = $\sqrt{2.32-1.536j}$, n_c = 1, λ = 1.55μm, respectively. The field amplitude has been normalized to a maximum value of unity.

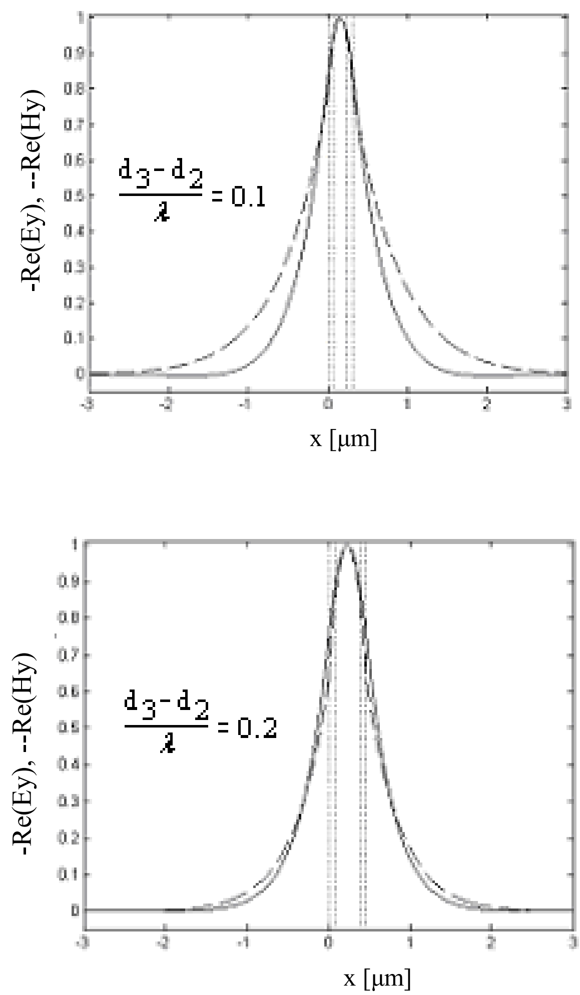

Fig. 2. The real part of the fundamental field profiles (E_y, H_y) for a waveguide with d_1 = 0μm, d_2 = 0.08μm, d_3 = 0.235μm, d_4 = 0.315μm, d/λ = 0.1, n_s = 1, $n_1 = \sqrt{2.32-1.536j}$, $n_2 = \sqrt{2.07}$, $n_3 = \sqrt{2.32-1.536j}$, n_c = 1, λ = 1.55μm and for a waveguide with d_1 = 0μm, d_2 = 0.08μm, d_3 = 0.235μm, d_4 = 0.315μm, d/λ = 0.2, n_s = 1, $n_1 = \sqrt{2.32-1.536j}$, $n_2 = \sqrt{2.07}$, $n_3 = \sqrt{2.32-1.536j}$, n_c = 1, λ = 1.55μm, respectively. The field amplitude has been normalized to a maximum value of unity.

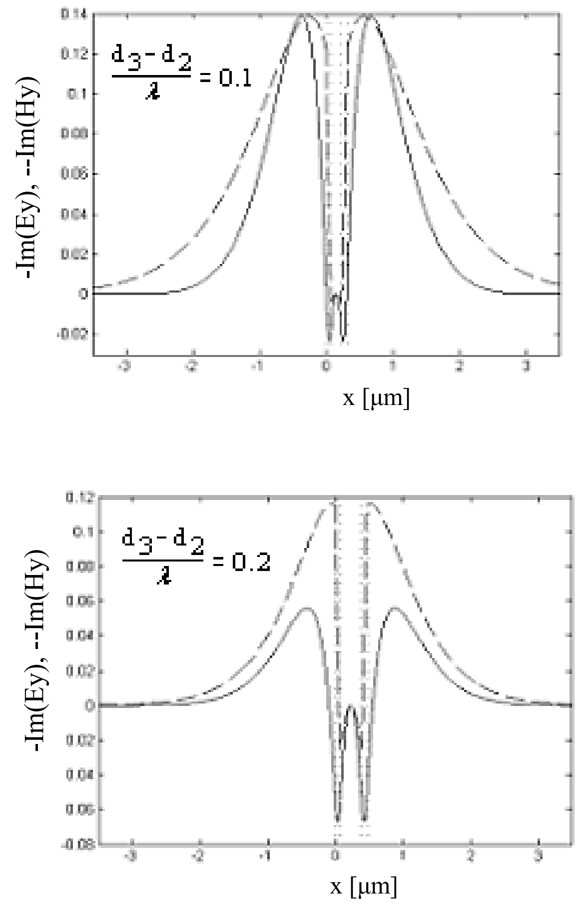

Fig. 3. The imaginary part of the fundamental field profiles (E_y, H_y) for a waveguide with d_1 = 0μm, d_2 = 0.08μm, d_3 = 0.235μm, d_4 = 0.315μm, d/λ = 0.1, n_s = 1, $n_1 = \sqrt{2.32-1.536j}$, $n_2 = \sqrt{2.07}$, $n_3 = \sqrt{2.32-1.536j}$, n_c = 1, λ = 1.55μm and for a waveguide with d_1 = 0μm, d_2 = 0.08μm, d_3 = 0.235μm, d_4 = 0.315μm, d/λ = 0.2, n_s = 1, $n_1 = \sqrt{2.32-1.536j}$, $n_2 = \sqrt{2.07}$, $n_3 = \sqrt{2.32-1.536j}$, n_c = 1, λ = 1.55μm, respectively. The field amplitude has been normalized to a maximum value of unity.

The variational exact solution (Eq. (1) can be written as an eigenvalue equation) of the scalar wave Eq. (1) is found from a functional [2, 3].

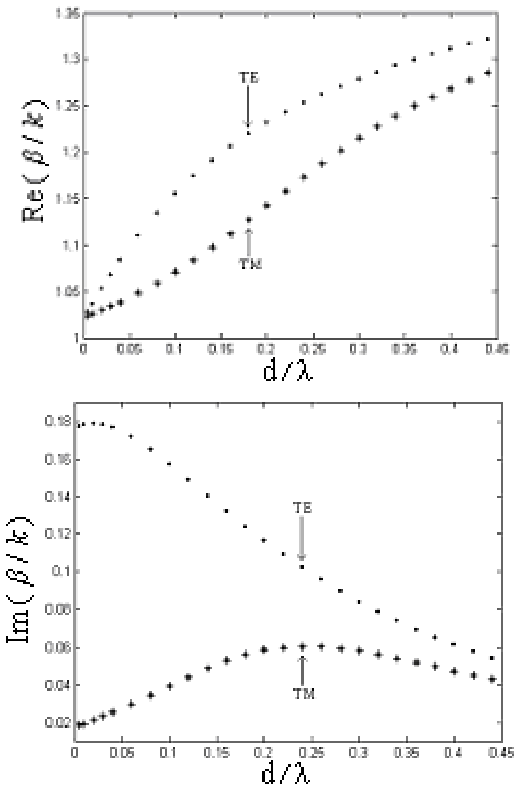

Fig. 4. The real and imaginary parts of the effective index versus d/ λ for TE and TM modes (d is the glass thickness).

The total power carried by the TE (TM) mode is related to the electric (magnetic) field through the relation [3]:

$$P = \frac{1}{2\omega\mu_0^{1-\xi}\varepsilon_0^{\xi}} \int_{-\infty}^{\infty} \mathrm{Re}\left[\beta \frac{|\psi(x)|^2}{n^{2\xi}(x)}\right] dx\,, \tag{3}$$

where ξ reads as 0 for TE ($\psi = E_y$) polarized waves and 1 for TM ($\psi = H_y$) polarized waves, μ_0 is the magnetic permeability of free space, ε_0 is the permittivity in a vacuum and ω is the angular frequency. The effect of the glass thickness on the confinement of the light in different parts of the waveguide structure is related to the fractional power P_i/P, where P_i is the power carried by a mode in a specific part of the waveguide.

3. Numerical results and conclusions

We have calculated the exact value of the effective index β/k for the guided modes in a waveguide (d_1 = 0μm, d_2 = 0.08μm, d_3 = 0.235μm, d_4 = 0.315μm, d / λ = 0.1, n_s = 1, n_1 = $\sqrt{2.32-1.536j}$, n_2 = $\sqrt{2.07}$, n_3 = $\sqrt{2.32-1.536j}$, n_c = 1, λ = 1.55μm) where a lossless substrate has refractive index lower than that of the lossy superconducting layers and for another waveguide substrate (d_1 = 0μm, d_2 = 0.08μm, d_3 = 0.235μm, d_4 = 0.315μm, d / λ = 0.2, n_s = 1, n_1 = $\sqrt{2.32-1.536j}$, n_2 = $\sqrt{2.07}$, n_3 = $\sqrt{2.32-1.536j}$, n_c = 1, λ = 1.55μm) with a larger thickness of the glass substrate. Figs. 1-3 show the real and imaginary parts of the fundamental field profiles (E_y, H_y) for these waveguides. The field amplitude has been normalized to a maximum value of unity. For these waveguides, the TM mode amplitude is more confined within the core layer and in superconducting thin films and more evanescent in the air claddings in comparison with the TE mode profile.

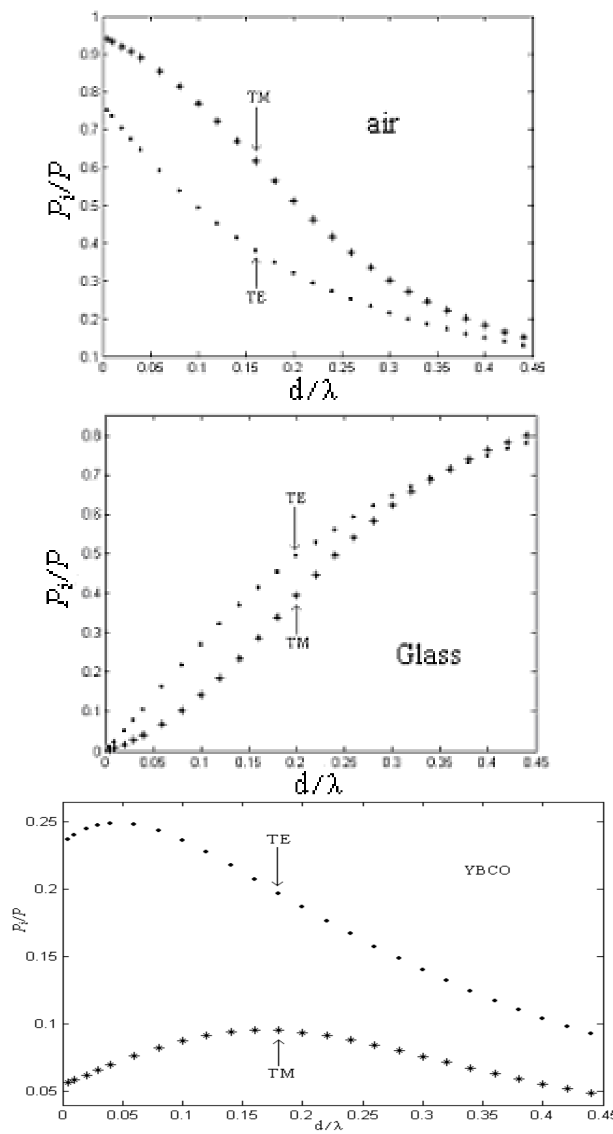

Fig. 5. The fraction of the power P_i /P, versus d/ λ, carried by the fundamental TE and TM modes in different parts of the waveguide structure (d is the glass thickness).

Fig. 4 shows the effect of thickening the glass layer on the real and imaginary parts of the effective index for TE and TM modes. If the thickness of the buffer layer is increased, the real part of the effective index is also increased. The imaginary part of the effective index shows a maximum at small values of the glass thickness for TE mode and at high values of the glass thickness for TM mode. The maximum for the imaginary part of the effective index for TM mode is smaller and shifted to higher values of the glass thickness in comparison with the TE mode.

Fig. 5 show the fraction of the power, versus the glass thickness, carried by the TE and TM modes (per unit length in y direction) along the z axis, for different parts of the waveguide structure. With an increase in the glass layer thickness, the fraction of the power in the air is diminished and the power is increased in the glass core layer. The fraction of the power guided in YBCO layers shows a maximum at small values of the glass thickness for TE mode and at high values of the glass thickness for TM mode. The maximum of the fractional power guided in superconducting layers for TM mode is smaller and shifted to higher values of the glass thickness in comparison with the TE mode.

Our analyses are important for engineering design of multilayer waveguides with layers consists of dielectric and superconducting materials.

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