

# Power absorption efficiency in plasmon - polariton optical superconducting planar and rib waveguides

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We analyze the power absorption efficiency for guided  $TM_0$  and  $TM_1$  modes and for leaky  $TM_0$  mode in plasmon – polariton superconducting traveling wave photo detectors. Also, the finite element method is applied to determine the optical propagation characteristics of the plasmon-polariton superconducting rib waveguides.

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## 1. Introduction

The knowledge of optical propagation characteristics of the plasmon-polariton optical superconducting waveguides is very important for the project of a new class of ultra sensitive, ultra fast and ultra slow noise detectors of light [1].

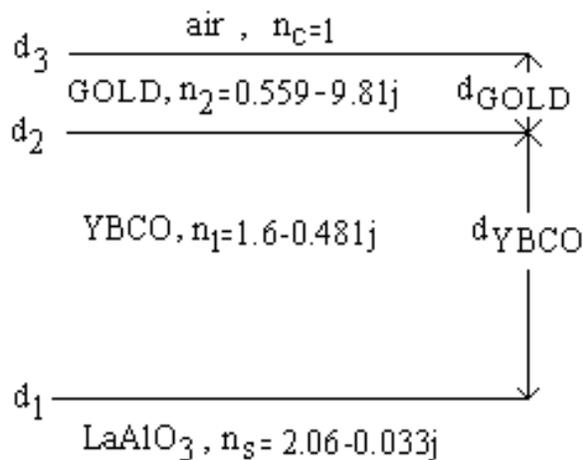


Fig.1. Schematic of a superconductor planar waveguide with  $d_1 = 0\mu\text{m}$ ,  $d_2 = d_{\text{YBCO}} = 0.1\mu\text{m}$ ,  $d_3 = 0.11\mu\text{m}$ ,  $d_{\text{GOLD}} = 0.01\mu\text{m}$  and for a superconductor planar waveguide with  $d_1 = 0\mu\text{m}$ ,  $d_2 = d_{\text{YBCO}} = 0.2\mu\text{m}$ ,  $d_3 = 0.21\mu\text{m}$ ,  $d_{\text{GOLD}} = 0.01\mu\text{m}$ .

The analyzed waveguide (Fig. 1) consists of a gold layer placed on a lossy superconductor (YBCO) layer and this structure is enclosed by air above and a semi-infinite substrate ( $\text{LaAlO}_3$ ) layer below.

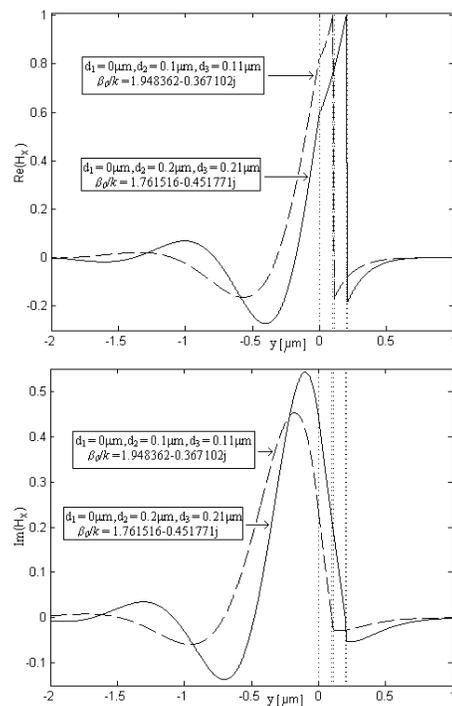


Fig. 2. The real and imaginary parts of the guided fundamental field profile  $TM_0$  for a waveguide ( $d_1 = 0\mu\text{m}$ ,  $d_2 = 0.1\mu\text{m}$ ,  $d_3 = 0.11\mu\text{m}$ ,  $d_{\text{GOLD}} = 0.01\mu\text{m}$ ,  $d_{\text{YBCO}} = 0.1\mu\text{m}$ ,  $n_s = 2.06-0.033j$ ,  $n_1 = 1.6-0.481j$ ,  $n_2 = 0.559 - 9.81j$ ,  $n_c = 1$ ,  $\lambda = 1.55\mu\text{m}$ ) and for a waveguide ( $d_1 = 0\mu\text{m}$ ,  $d_2 = 0.2\mu\text{m}$ ,  $d_3 = 0.21\mu\text{m}$ ,  $d_{\text{GOLD}} = 0.01\mu\text{m}$ ,  $d_{\text{YBCO}} = 0.2\mu\text{m}$ ,  $n_s = 2.06-0.033j$ ,  $n_1 = 1.6-0.481j$ ,  $n_2 = 0.559 - 9.81j$ ,  $n_c = 1$ ,  $\lambda = 1.55\mu\text{m}$ ). The fractions of the power in  $\text{LaAlO}_3$ , YBCO, gold and air are 0.51, 0.46, 0.00, 0.03, for the first waveguide and 0.36, 0.61, 0.00, 0.04 for the second waveguide, respectively. The field amplitude has been normalized to a maximum value of unity.

The effective index of surface plasmon-polariton mode along the gold-air, gold-YBCO and gold-LaAlO<sub>3</sub> interfaces is  $1.005185-0.000597j$ ,  $1.613183-0.501719j$  and  $2.106171-0.040778j$ , respectively. Thus in function of the thickness of the gold and YBCO layers, we expect two (TM<sub>0</sub> and TM<sub>1</sub>) guided modes for our structure. The leaky modes for this waveguide structure are also expected because the real part of the refractive index for the substrate layer is very large. Thus, a large portion of optical power is absorbed by the YBCO layer for TM<sub>0</sub> mode and unfortunately another great portion of power for guided TM<sub>1</sub> and leaky TM<sub>0</sub> modes is absorbed by the air and substrate layers.

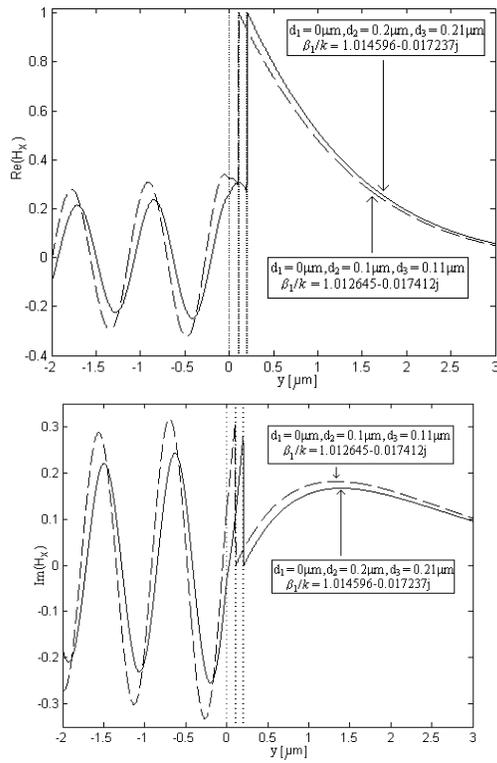


Fig. 3. The real and imaginary parts of the guided magnetic field profile TM<sub>1</sub> for a waveguide ( $d_1 = 0\mu\text{m}$ ,  $d_2 = 0.1\mu\text{m}$ ,  $d_3 = 0.11\mu\text{m}$ ,  $n_s = 2.06-0.033j$ ,  $n_1 = 1.6-0.481j$ ,  $n_2 = 0.559-9.81j$ ,  $n_c = 1$ ,  $\lambda = 1.55\mu\text{m}$ ) and for a waveguide ( $d_1 = 0\mu\text{m}$ ,  $d_2 = 0.2\mu\text{m}$ ,  $d_3 = 0.21\mu\text{m}$ ,  $n_s = 2.06-0.033j$ ,  $n_1 = 1.6-0.481j$ ,  $n_2 = 0.559-9.81j$ ,  $n_c = 1$ ,  $\lambda = 1.55\mu\text{m}$ ). The fractions of the power in LaAlO<sub>3</sub>, YBCO, gold and air are 0.15, 0.01, 0.00, 0.84, for the first waveguide and 0.10, 0.01, 0.00, 0.89 for the second waveguide, respectively. The field amplitude has been normalized to a maximum value of unity.

In this paper we analyze the power absorption efficiency for guided TM<sub>0</sub> and TM<sub>1</sub> modes and for leaky TM<sub>0</sub> mode in plasmon – polariton superconducting traveling wave photo detectors. Also, the finite element method is applied to determine the characteristics of the plasmonic optical superconducting rib waveguides.

## 2. Plasmon polariton superconductor optical planar waveguide

The scalar-wave equation for a slab waveguide is given by

$$\frac{d^2\psi(y)}{dy^2} + k^2 n^2(y)\psi(y) = \beta^2\psi(y), \quad (1)$$

where  $\beta$  is the propagation constant,  $k$  is the free space wave number,  $n(y)$  is the refractive index profile

$$n(y) = \begin{cases} n_s, & \text{for } y < d_1 = 0, \\ n_i, & \text{for } d_i < y < d_{i+1}, i = 1, 2, \\ n_c, & \text{for } d_3 < y, \end{cases} \quad (2)$$

$n_s$ ,  $n_1$ ,  $n_2$ , and  $n_c$  are the refractive index of the LaAlO<sub>3</sub> substrate, YBCO film, gold layer and air cladding, respectively. The effective index  $\beta/k$  for TM modes can be found from the dispersion equation which is obtained by applying the boundary conditions at the interfaces between different layers.

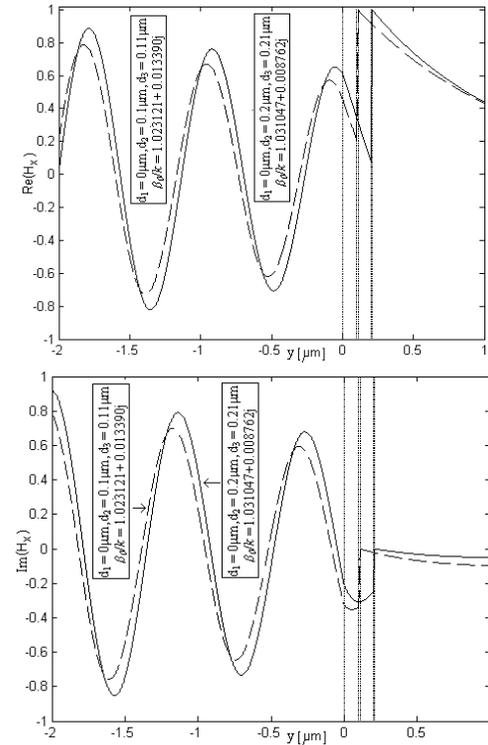


Fig. 4. The real and imaginary parts of the leaky magnetic field profile TM<sub>0</sub> for a waveguide ( $d_1 = 0\mu\text{m}$ ,  $d_2 = 0.1\mu\text{m}$ ,  $d_3 = 0.11\mu\text{m}$ ,  $n_s = 2.06-0.033j$ ,  $n_1 = 1.6-0.481j$ ,  $n_2 = 0.559-9.81j$ ,  $n_c = 1$ ,  $\lambda = 1.55\mu\text{m}$ ) and for a waveguide ( $d_1 = 0\mu\text{m}$ ,  $d_2 = 0.2\mu\text{m}$ ,  $d_3 = 0.21\mu\text{m}$ ,  $n_s = 2.06-0.033j$ ,  $n_1 = 1.6-0.481j$ ,  $n_2 = 0.559-9.81j$ ,  $n_c = 1$ ,  $\lambda = 1.55\mu\text{m}$ ). The field amplitude has been normalized to a maximum value of unity.

The variational exact solution [2] of the scalar wave Eq. (1) is found from the functional

$$J_{11} = \int_{-\infty}^{d_1} \left[ -\frac{f_s'^2}{n_s^2} + (kf_s)^2 \right] dy + \sum_{i=1}^2 \int_{d_i}^{d_{i+1}} \left[ -\frac{f_i'^2}{n_i^2} + (kf_i)^2 \right] dy + \int_{d_3}^{\infty} \left[ -\frac{f_c'^2}{n_c^2} + (kf_c)^2 \right] dy, \quad (3)$$

subject to the constraint that

$$I_{11} = \int_{-\infty}^{d_1} \frac{f_s^2}{n_s^2} dy + \sum_{i=1}^2 \int_{d_i}^{d_{i+1}} \frac{f_i^2}{n_i^2} dy + \int_{d_3}^{\infty} \frac{f_c^2}{n_c^2} dy, \quad (4)$$

$$\beta^2 = \frac{J_{11}}{I_{11}} \quad (5)$$

where the exact functions  $f_s$ ,  $f_i$  and  $f_c$  are given by

$$\begin{aligned} f_s(y) &= A_s \exp(a_s y), & y < d_1, \\ f_i(y) &= A_i \cos[a_i(y - d_i)] + B_i \sin[a_i(y - d_i)], & d_i < y < d_{i+1}, i=1,2, \\ f_c(y) &= A_c \exp(-a_c(y - d_3)), & y > d_3, \end{aligned} \quad (6)$$

and

$$a_s = \pm \sqrt{\beta^2 - (n_s k)^2}, a_i = \sqrt{(n_i k)^2 - \beta^2}, a_c = \sqrt{\beta^2 - (n_c k)^2}, i=1,2, \quad (7)$$

$$A_1 = A_s = 1, B_1 = \frac{n_1^2 a_s}{n_s^2 a_1},$$

$$A_i = A_{i-1} \cos[a_{i-1}(d_i - d_{i-1})] + B_{i-1} \sin[a_{i-1}(d_i - d_{i-1})], i=1,2,$$

$$B_i = \frac{n_i^2 a_{i-1}}{n_{i-1}^2 a_i} (B_{i-1} \cos[a_{i-1}(d_i - d_{i-1})] - A_{i-1} \sin[a_{i-1}(d_i - d_{i-1})]), i=1,2,$$

$$A_c = A_2 \cos[a_2(d_3 - d_2)] + B_2 \sin[a_2(d_3 - d_2)] \quad (8)$$

The minus (plus) sign for  $a_s$  corresponds to the leaky (guiding) modes in substrate.

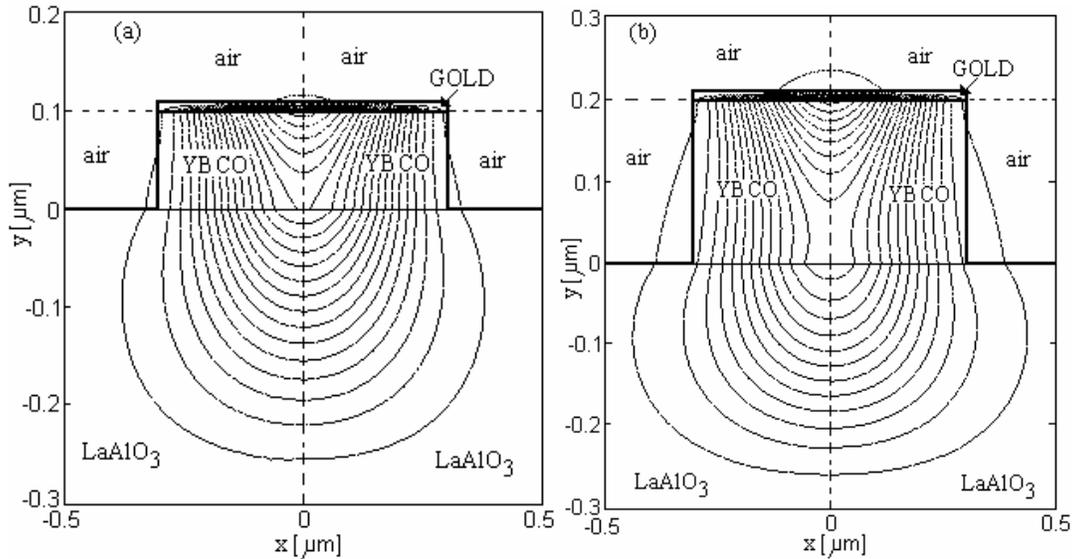


Fig. 5. Contour plot of the intensity distribution  $|\Psi(y)|^2$  of the fundamental magnetic field in a superconductive rib waveguide for fixed values of the gold layer thickness  $d_{\text{GOLD}} = 0.01 \mu\text{m}$  and ridge width  $w = 0.6 \mu\text{m}$ , and for two values of the YBCO layer thickness: (a)  $d_{\text{YBCO}} = 0.1 \mu\text{m}$ ,  $\beta_0/k = 1.595711 - 0.490658j$  and (b)  $d_{\text{YBCO}} = 0.2 \mu\text{m}$ ,  $\beta_0/k = 1.430263 - 0.522088j$ . The dashed horizontal lines correspond to the maximum of the field distribution at  $y = 0.1 \mu\text{m}$  and  $y = 0.2 \mu\text{m}$ .

The solutions of the dispersion equation (5)

$$\frac{J_{11}}{I_{11}} - \beta^2 = 0 \quad (9)$$

give the propagation constants  $\beta$  and the effective index  $\beta/k$  of the waveguide.

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

$$P = \frac{1}{2\omega\epsilon_0} \int_{-\infty}^{\infty} \text{Re} \left[ \beta \frac{|\psi(y)|^2}{n^2(y)} \right] dy, \quad (10)$$

where  $\psi = H_x$ ,  $\epsilon_0$  is the permittivity in a vacuum and  $\omega$  is the angular frequency.

### 3. Numerical results and conclusions

We have calculated the exact value of the effective index  $\beta/k$  for the guided mode  $\text{TM}_0$  in a waveguide (Fig.1

with  $d_1 = 0\mu\text{m}$ ,  $d_2 = d_{\text{YBCO}} = 0.1\mu\text{m}$ ,  $d_3 = 0.11\mu\text{m}$ ,  $d_{\text{GOLD}} = 0.01\mu\text{m}$ ,  $n_s = 2.06-0.033j$ ,  $n_1 = 1.6-0.481j$ ,  $n_2 = 0.559 - 9.81j$ ,  $n_c = 1$ ,  $\lambda = 1.55\mu\text{m}$ ,  $\beta_0/k = 1.948362-0.367102j$ ) and for a waveguide (Fig.1 with  $d_1 = 0\mu\text{m}$ ,  $d_2 = d_{\text{YBCO}} = 0.2\mu\text{m}$ ,  $d_3 = 0.21\mu\text{m}$ ,  $d_{\text{GOLD}} = 0.01\mu\text{m}$ ,  $n_s = 2.06-0.033j$ ,  $n_1 = 1.6-0.481j$ ,  $n_2 = 0.559 - 9.81j$ ,  $n_c = 1$ ,  $\lambda = 1.55\mu\text{m}$ ,  $\beta_0/k = 1.761516-0.451771j$ ). Fig. 2 shows the real and imaginary parts of the fundamental field profiles  $\text{TM}_0$  for these waveguides. The field amplitude has been normalized to a maximum value of unity.

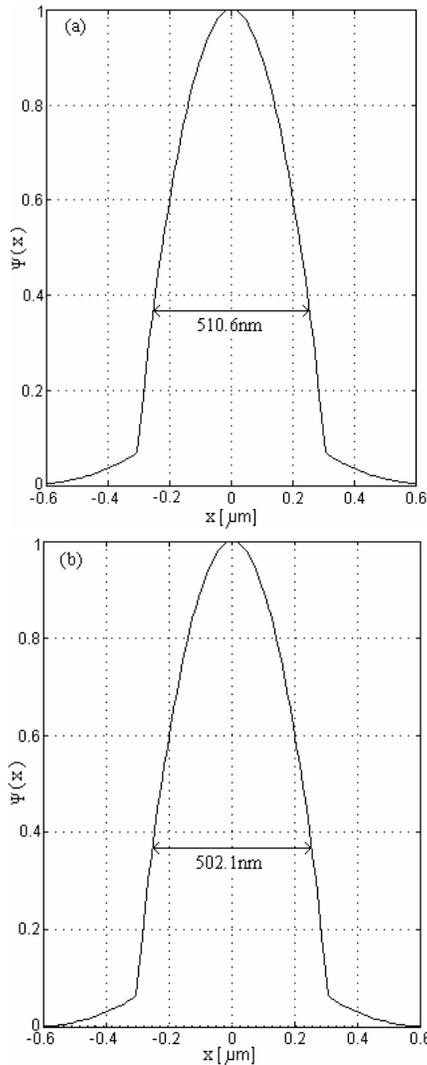


Fig. 6. Cross section of the fundamental magnetic field (real part) in superconducting rib waveguides from Fig.5. The mode widths at  $1/e$  in the  $x$  direction are 510.6nm and 502.1nm, respectively.

The fractions of the power in  $\text{LaAlO}_3$ , YBCO, gold and air are 0.51, 0.46, 0.00, 0.03, for the first waveguide and 0.36, 0.61, 0.00, 0.04 for the second waveguide, respectively. Also, we have calculated the exact value of the effective index  $\beta/k$  for the guided mode  $\text{TM}_1$  and for the leaky mode  $\text{TM}_0$  in the same waveguides. Figs. 3 - 4 show the real and imaginary parts of the guided magnetic

field profile  $\text{TM}_1$  and for single leaky mode  $\text{TM}_0$ . The fractions of the power for the guided mode  $\text{TM}_1$  in  $\text{LaAlO}_3$ , YBCO, gold and air are 0.15, 0.01, 0.00, 0.84, for the first waveguide and 0.10, 0.01, 0.00, 0.89 for the second waveguide, respectively. Fig. 2 shows that by increasing the thickness of the active YBCO layer from 0.1 $\mu\text{m}$  to 0.2 $\mu\text{m}$ , the power absorption efficiency for  $\text{TM}_0$  mode in this layer is increased. Figs. 3 - 4 show that a large part of the fractional power is lost in air for guided  $\text{TM}_1$  and leaky  $\text{TM}_0$  modes. Comparing the results with those in [1], we report a typographical error in [1] regarding the values of the effective index  $\beta/k$  at a wavelength of 1550 $\mu\text{m}$  for the fundamental  $\text{TM}_0$  mode of a waveguide in which the thickness of the superconducting and gold layers are 100nm and 10nm, respectively. Thus, the correct value is  $\beta_0/k = 1.948362-0.367102j$  and not  $\beta_0/k = 1.9613-0.4347j$ . Also, for a waveguide with  $d_{\text{YBCO}} = 200\text{nm}$  and  $d_{\text{GOLD}} = 10\text{nm}$ , the coupling efficiency is 61% and not 90%.

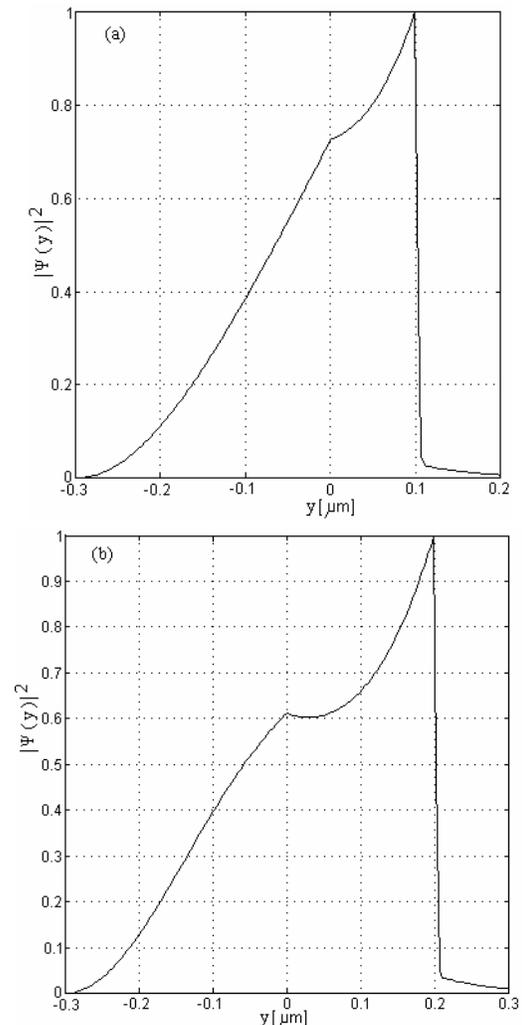


Fig. 7 Cross section of the intensity vertical distribution  $|\Psi(y)|^2$  of the fundamental magnetic field in superconducting rib waveguides from Fig.5.

Also, the finite element method is applied to determine the optical propagation characteristics of the plasmon-polariton superconducting rib waveguides. Fig.5 shows a contour plot of the intensity distribution  $|\Psi(y)|^2$  of the fundamental magnetic field in a superconductive rib waveguide for fixed values of the gold layer thickness  $d_{\text{GOLD}} = 0.01\mu\text{m}$  and ridge width  $w = 0.6\mu\text{m}$ , and for two values of the YBCO layer thickness: (a)  $d_{\text{YBCO}} = 0.1\mu\text{m}$ ,  $\beta_0/k = 1.595711-0.490658j$  and (b)  $d_{\text{YBCO}} = 0.2\mu\text{m}$ ,  $\beta_0/k = 1.430263-0.522088j$ . Fig.6 shows a cross section of the fundamental magnetic field (real part) in superconducting rib waveguides from Fig. 5. The mode widths at  $1/e$  in the x direction are 510.6nm and 502.1nm, respectively. Fig. 7 shows a cross section of the intensity vertical distribution  $|\Psi(y)|^2$  of the fundamental magnetic field in superconducting rib waveguides from Fig. 5.

Our analyses are important for engineering project of multilayer waveguides with layers consisting of dielectric, metal and superconducting materials.

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