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# Characteristics of surface plasmon polaritons in ZnO based nanowaveguides

Deepu Thomas [a], R. Ajith [b], C. Bhagyaraj [c,d], Vincent Mathew [b,*], Simon Augustine [c]

[a] Research and Development Centre, Bharathiar University, Coimbatore 641046, India
[b] Department of Physics, Central University of Kerala, Nileshwar, Kasaragode, Kerala 671314, India
[c] Postgraduate and Research Department of Physics, St. Thomas College, Palai, Kerala 686574, India
[d] Department of Physics, St. Mary's College, Sulthan Bathery, Wayanad, Kerala 673592 India

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ABSTRACT

In this paper dispersion characteristics of fundamental surface plasmon polariton modes supported by ZnO (zinc oxide) strip and slab waveguides were studied. It is observed from the dispersion studies that Ga:ZnO strip waveguide supports four fundamental modes which are non-degenerate in nature. The guiding properties of waveguide suggest ZnO films with high carrier concentration as a good substitute for metals in future integrated optoelectronic devices.



## 1. Introduction

Surface plasmon polaritons (SPP) propagating through conductor/dielectric interface enriched the development of nano scale optoelectronic devices in the past [1,2]. Majority of devices based on SPP chose metal as the conductor medium. One of the major problems that occur in metal based plasmonic devices is the high optical losses in the near-infrared (NIR) and visible spectral ranges [1]. Another limitation is that devices based on metals have limited tuning capabilities. Also metals were found to be less compatible with advanced device integration technologies. These limitations can be overcome by using heavily doped semiconductors as a substitute to metals in plasmonic elements. ZnO (Zinc Oxide) has been found to be a suitable candidate with its promising optical and electrical properties [2].

ZnO is a compound semiconductor with direct band-gap of 3.2 eV and is completely transparent in the infrared spectral range except at the Reststrahlen band [3]. The benefits of using ZnO in plasmonics are low intrinsic loss, semiconductor-based design, tenability, low-cost, etc. [2]. ZnO is a versatile material that develops various properties like piezoelectricity, ferroelectricity, ferromagnetism upon doping by trivalent dopants such as aluminum and gallium [4–6]. Gallium doping is reported to produce Ga:ZnO (gallium doped ZnO) films with high carrier concentration and mobility. These films also show metal-like optical properties such as negative dielectric permittivity and high reflectivity in the IR region [5]. It is reported that heavily doped Ga:ZnO have losses four times smaller than silver at 1.5 μm wavelength (telecommunication wavelength) and this find application in photonics [7]. In this paper we analyzed the dispersion characteristics of slab waveguide structure with Ga:ZnO as a layer. Then slab was replaced with a strip structure to effectively increase the field confinement of the

* Corresponding author.
*E-mail address:* deepuskariankal@gmail.com (D. Thomas).

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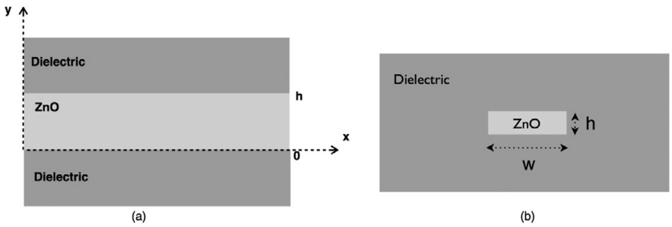


**Fig. 1.** Geometry of the waveguide: (a) slab waveguide and (b) strip waveguide.

mode. The dependence of four fundamental modes supported by the strip waveguide on the strip thickness was analyzed. Section 2 gives a brief outline of the theory. Section 3 discusses the important results obtained.

## 2. Theory

The waveguide geometry considered consists of an ZnO film of thickness $h$ sandwiched between two dielectric (insulating) media with permittivity $\epsilon_1$ and $\epsilon_2$ respectively (Fig. 1(a)). From the time-harmonic vectorial wave equation for T M mode, the magnetic field component can be obtained. The nonvanishing field components at each interface are,

$$H_x(y,z,t) = e^{j(\omega t - \beta z)} H_0(y) \tag{1}$$

$$H_0(y) = \begin{cases} Ae^{-k_1 y} & : y > h \\ Be^{k_m y} \pm Ce^{-k_m y} & : 0 < y < h \\ De^{k_2 y} & : y < 0 \end{cases}$$

where

$$\begin{aligned} k_1 &= \sqrt{\beta^2 - \omega^2 \mu_0 \epsilon_0 \epsilon_1}, \quad y > h \\ k_m &= \sqrt{\beta^2 - \omega^2 \mu_0 \epsilon_0 \epsilon_m}, \quad 0 < y < h \\ k_2 &= \sqrt{\beta^2 - \omega^2 \mu_0 \epsilon_0 \epsilon_2}, \quad y < 0 \end{aligned} \tag{2}$$

where

$$\nabla \times \mathbf{H} - i\omega\epsilon\epsilon_0 \mathbf{E} = 0 \tag{3}$$

Demanding continuity of the electric and magnetic field components $H_x$ and $E_z$ across the interfaces ($y = 0$ and $y = h$) gives the following dispersion relation:

$$\tanh(k_m h) = -\frac{\frac{k_m}{\epsilon_m}\left(\frac{k_1}{\epsilon_1} + \frac{k_2}{\epsilon_2}\right)}{\frac{k_m^2}{\epsilon_m^2} + \left(\frac{k_1}{\epsilon_1}\frac{k_2}{\epsilon_2}\right)} \tag{4}$$

$$\coth(k_m h) = -\frac{\frac{k_m}{\epsilon_m}\left(\frac{k_1}{\epsilon_1} + \frac{k_2}{\epsilon_2}\right)}{\frac{k_m^2}{\epsilon_m^2} + \left(\frac{k_1}{\epsilon_1}\frac{k_2}{\epsilon_2}\right)} \tag{5}$$

Propagation constant of the fundamental modes supported by the slab structure is obtained by solving this dispersion relation. Next, the structure was modified by replacing the Ga:ZnO slab with an Ga:ZnO strip (Fig. 1(b)) to have better confinement for the surface plasmon polariton modes. Due to the inhomogeneity of the structure along two dimensions problem is unsolvable analytically. Hence, dispersion characteristics of the fundamental modes are obtained using finite element (FEM) method. We have used FEM based commercial software Comsol Multiphysics [4].

## 3. Results and discussion

The dispersion characteristics of the slab waveguide were studied analytically. The Ga:ZnO slab was sandwiched between two dielectric layers of permittivity $\epsilon_1 = \epsilon_2 = 3.6$. The material parameters of the present study are taken from the data in [1]. Fig. 2 shows the variation of normalized phase constant with wavelength of a fundamental mode supported by the slab waveguide. From figure, it can be seen that as the wavelength increases, the phase constant increases. Study was performed