RF ENZ Dielectric Waveguide

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Abstract

Recently, it has been shown possible to tunnel the flow of EM energy trough a slab (or a rod) made out of an ENZ material, transversal dimension of which can be arbitrarily smaller than a wavelength. Here, a complementary structure (a dielectric slab of subwavelength thickness), embedded within an ENZ metamaterial) is analyzed. Numerical results revealed behaviour similar to the behaviour of an ordinary dielectric waveguide, but with considerably longer guiding wavelength (for a fixed width of a core slab). Numerical analysis is complemented by the measurements on the RF scaled replica of an ENZ waveguide, operating in 4 GHz frequency band.

1. Introduction

The simplest dielectric waveguide is well known guiding structure that comprises a slab, relative permittivity of which is higher than permittivity of surrounding medium [1]. This structure has been known for a couple of decades and its several variants are widely used in the technology of optical fibres. However, recent introduction of the ENZ (Epsilon Near Zero) metamaterial [2] put forward several novel interesting ideas. In [3] it was proposed to guide the EM energy through a slab (or a rod) of an ENZ material, transversal dimension of which can be arbitrarily smaller than a wavelength. This 'tunnelling' effect might lead to several new applications such as the dielectric sensing [4] and an image transport with a subwavelength resolution [5]. Another very interesting proposal deals with 'D-dot wire' [6], which is optical analog of an ordinary wire. However, instead of a directional flow of conducting current, one deals with a directional flow of a displacement current ($\partial D/ \partial t$). Thus, the conductor that is present in an ordinary wire is replaced with an isotropic ENZ dielectric medium in D-dot wire. Full wave simulations of a TM propagation in such a structure [6], as well as the experiments in RF regime [7], indeed have proven the wire like behaviour, i.e. the existence of a directional flow of a displacement current. The structures used in all these proposals can be thought of being an 'inverted' dielectric waveguide (a dielectric waveguide with a core whose relative permittivity is lower than a relative permittivity of a surrounding medium (cladding). Following this basic idea, we investigate an opposite case – a 'classical' dielectric slab waveguide with ENZ cladding.

2. Theoretical and Experimental investigation of an ENZ waveguide

Let us analyze the structure from Fig. 1. It comprises two solid (green) bricks that represent a hypothetical continuous ENZ material with Drude dispersion model. The gap between the bricks act as an air core. The structure is considered as being infinite in vertical and horizontal directions. At first, the propagation factor k_z (and the guiding wavelength, $\lambda_g = 2\pi / k_z$) was obtained analytically using standard theory of dielectric slab waveguide [1]. Fig. 2 depicts calculated guiding wavelength as the function of the cladding permittivity, with the core (gap) width as a parameter. It can be noticed that (as in the case of an ordinary dielectric waveguide) the guiding wavelength increases with the decrease of the core width. This increase is not pronounced for the small values of the dielectric contrast (a ratio

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between relative permittivity of the dielectric core and the relative permittivity of the cladding). However, when the relative permittivity of the cladding slabs approaches zero (i.e. when the frequency approaches the plasma frequency (f_p), the guiding wavelength (λ_g) becomes very long. For instance, for the core width of 2.5 mm, the guiding wavelength is 50 cm, which is approximately seven times longer than the free-space wavelength. So, this ENZ dielectric waveguide operating in TE mode might be used for the applications that require long guiding wavelength (such as dielectric sensing [4]).

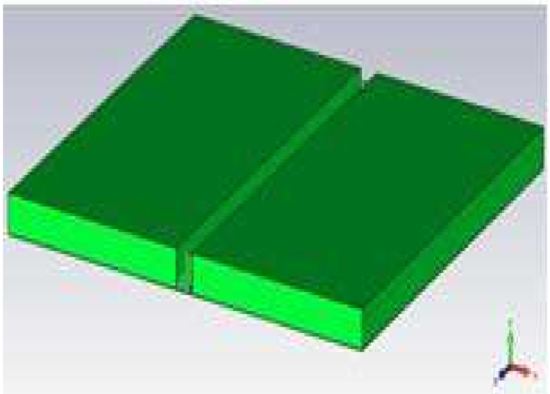

Fig. 1: An ENZ dielectric waveguide with air gap (core).

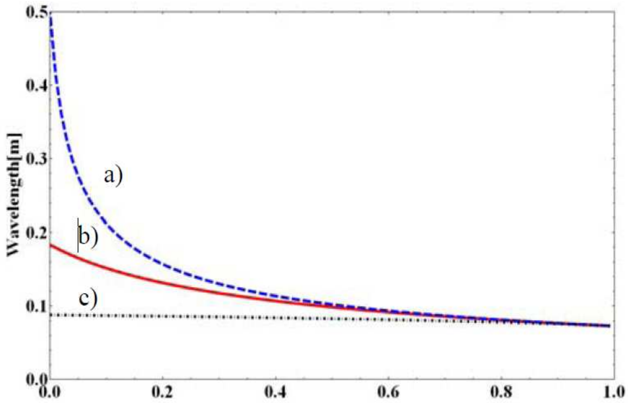

Fig. 2: Calculated guiding wavelength for the homogenous model of the ENZ waveguide from Fig 1. The gap widths are: a) 2.5 mm, b) 10 mm, c) 40 mm. The dispersion parameters of Drude model of an ENZ material are: f_0=1.86GHz, f_p=4.12GHz, γ=100 MHz). The free-space wavelength (at fp) is 7.28 cm.

In order to test analytical results, an RF replica of the ENZ waveguide was manufactured (Fig.3). Thus, a metamaterial with ENZ behaviour was needed. It comprises an array of inductively loaded short dipoles that acts as an ENZ slab. The array was designed with the help of commercial full wave simulator CST^{TM} Microwave Studio [8] and manufactured in PCB technology (Fig. 3). Each particular unit cell comprised a 10x10 mm patch etched on the 1.6 mm thick FR-4 substrate with the copper cladding. The distance between each patch and the neighbouring patches was 1mm. The array of patches was mounted on a 10 mm thick foam slab (ε_r~1). Another FR-4 plate with copper cladding was put beneath the foam. A small hole (diameter of 1 mm) was drilled in the centre of each patch, protruding the foam slab and a second FR-4 plate (operating as a ground plane). Then, a piece of 0.6 mm thick copper wire was inserted into a hole of each patch, through the foam slab and a ground plane. The wire was soldered both on the patch side and on the ground plane side making an array of inductively loaded monopole antennas (the mushrooms). The four blocks of mushrooms were manufactured: two blocks with 9 x 17 mushrooms and one block with 6 x 17 mushrooms. Each block of mushrooms can easily be used as an array of inductively loaded dipoles. To this end one should add a second foam slab (thickness of 10 mm) with the ground plane on the top of patches. This structure (operating slightly above the series resonance of the dipoles) should behave as an uniaxial ENZ slab with the plasma frequency (f_p) of 4 GHz.

In the first experiment, an analog of the ENZ waveguide was assembled out of four mushroom blocks (left part of Fig. 3). The ground planes of the mushroom blocks were connected with a conducting copper tape. One mushroom-free row was acting as an air gap (a core slab). The length of the gap was 20.2 cm (equal to the length of two side placed blocks). The RF replica of ENZ waveguide was equipped with two short monopole antennas (N connectors with the inner pins length of 14 mm), and transmission coefficient was measured with the help of HP 8720B network analyzer (Fig.4). It can be seen that the transmission pass-band, consisted with theoretical predictions, appeared at the frequency of 4 GHz (plasma frequency). This is in very good agreement with the calculated value of plasma frequency (4.12 GHz). Pronounced attenuation at the frequencies lower than 4 GHz can be explained with the negative value of the equivalent permittivity of the ENZ metamaterial. In the next step, the distribution of the phase of the transmission coefficient along the air gap was measured. For this measurement, the 3 mm wide slot was cut along the copper tape that closes the gap. The waveguide was excited at one side, while the small probe was moved along the gap. The phase of S_{21} parameter was measured at 10 equally spaced points. It was assumed that there was no reflection from the far end of the waveguide, due to losses in FR-4 substrate. Therefore, only the incident wave existed within the gap and it was possible to calculate the guiding wavelength (the length at which a phase of transmission coefficient changes by 2π) . Obtained result of 21 cm was again in very good agreement with theoretical value of 19 cm (Fig. 2.). Thus, the measured guiding wavelength was indeed significantly longer than a free space wavelength (7.28 cm).

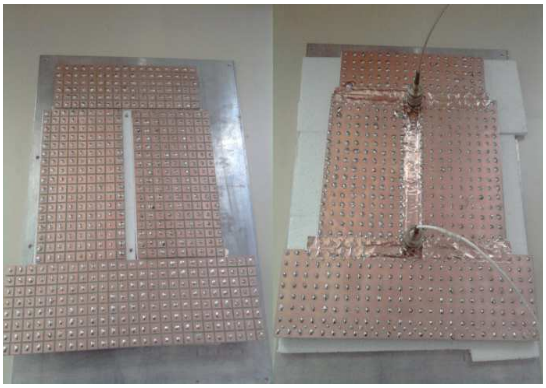

Fig. 3: Experimental RF replica of an ENZ waveguide. Left: The top side (aluminium plate acting as a ground plane was removed), Right: The bottom side with monopole antennas.

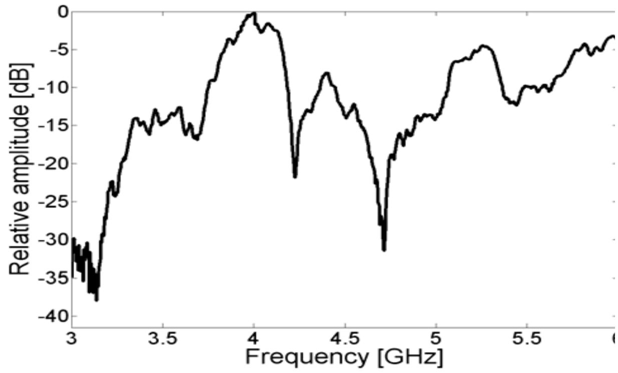

Fig. 4: Measured transmission coefficient of the experimental RF replica of ENZ waveguide (the plot is normalized to the maximal value).

3. Conclusion

In this paper, a dielectric waveguide with an ENZ metamaterial cladding and a free space core was proposed and a scaled RF replica, operating in 4 GHz frequency band, was manufactured. Series of numerical simulations and associated experiments proved that this structure supports propagation of the electromagnetic energy in TE mode, in spite of the subwavelength width of the air core. Narrowing of the core resulted in an increase of the wavelength and the phase velocity of the EM wave inside the core. The guiding wavelength of this peculiar waveguide is always considerably longer than a guiding wavelength in ordinary dielectric waveguide.

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