Experimental verification of wideband tuning of the tunnelling frequency in ENZ channel

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Abstract

In this paper we propose a novel design of ε-near-zero (ENZ) waveguide consisting of a microwave substrate which serves as a channel and as a carrier for input foam waveguides. A novel method for shifting the tunnelling frequency by using two longitudinal slots on the broad side of the channel was also proposed. In the end, experimental verification is presented. Shift of the tunnelling frequency Δf=300 MHz (6.79-6.49 GHz) was observed after adding slots.

1. Introduction

Energy tunnelling through a very narrow channel obtained by reducing the height of a rectangular waveguide has attracted a great deal of attention in the research community in the last few years. It was theoretically shown [1-2] that a narrow waveguide channel would support very narrow transmission of an incident signal despite of a great mismatch caused by E-plane step discontinuity. It was explained [3] that such an unusual transmission called “tunnelling” appears near the cut-off frequency of the channel, when its effective permittivity becomes close to zero (epsilon-near-zero, ENZ). The tunnelling frequency does not depend on the length of the ENZ channel, but only on the permittivity of the channel and its width.

The nonlinear control of tunnelling frequency by changing the capacitance of a varactor diode placed into the channel was proposed earlier in [4]. However, the obtained frequency shift was accompanied with considerable reduction of transmission amplitude and quality factor for higher values of varactor capacitance, which is the main drawback of this method. In this paper we propose a novel design of the ENZ channel, and also a novel and efficient method for the wideband tuning of tunnelling frequency. The shift of the tunnelling frequency is obtained by means of varying the lengths of two longitudinal slots placed at the very ends of the channel. This way of tuning does not influence transmission amplitude considerably, and can be applied efficiently to very narrow channels.

2. Novel design of ENZ waveguide with reduced width of the channel

Novel design of ENZ waveguide is shown in Fig. 1, with relevant dimensions: width a=22 mm, channel width a_{ch}=15 mm, height b=11 mm, and channel height b_{ch}=0.508 mm. The ENZ waveguide consists of a thin microwave substrate CuFlon (ε_r=2.1, $tg\delta$=0.001) which is used as an ENZ channel, and also as a carrier for input waveguides. The use of the microwave substrate as a channel is the main advantage of this design, because it allows precise control of the channel height and metal roughness, which greatly affect transmission losses. Input waveguides are made from a foam dielectric ROHACELL 200WF ($\varepsilon_r^{)}$=1.22 and $tg\delta^{)}$=0.0009) which is easily shaped and cut. To allow tunnelling, channel permittivity (ε_{ch}) should be lower than in the input waveguides (ε_{wg}), as it was stated in all previous published papers dealing with ENZ waveguides. In this paper we demonstrate the design of ENZ wa-

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veguide with ε_{ch} higher than ε_{wg}, which requires that the channel width becomes lower than the width of the input waveguides.

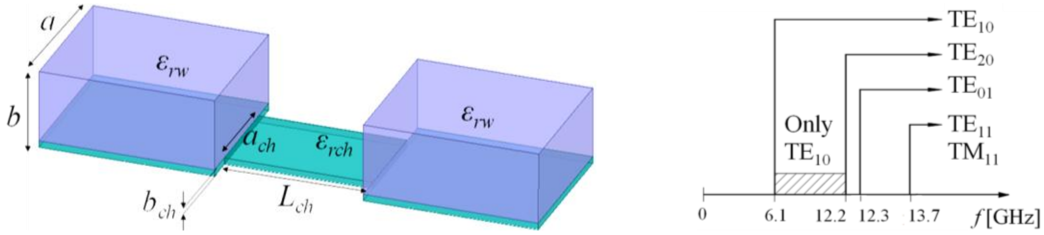

Fig. 1: a) Novel design of ENZ waveguide (metal coating is removed for the sake of clarity); b) Frequency distribution of the first five modes in input waveguides with their cut-off frequencies.

According to [3], propagation of TE_{10} mode in a narrow channel can be described as a propagation of TEM mode in parallel-plate waveguide with effective permittivity ε_{reff}:

$$\beta_{TE10} = \sqrt{k^2 - (\pi / a_{ch})^2} = \beta_{TEM} = \frac{2\pi f\sqrt{\varepsilon_{reff}}}{c} \Rightarrow \varepsilon_{reff} \cong \varepsilon_{rch} - \frac{c^2}{4f^2 a_{ch}{}^2}, \qquad \beta_{eff} = \frac{2\pi f\sqrt{\varepsilon_{reff}}}{c},\ k = \frac{2\pi f\sqrt{\varepsilon_{rch}}}{c}. \tag{1}$$

Here c is the speed of light in vacuum and ε_{rch} is a relative dielectric constant in the channel. It is seen that ε_{reff} equals zero at the cut-off frequency of the channel, where tunnelling of energy occurs (2). In our case tunnelling occurs at the frequency f_{tun}=6.9 GHz, which is in a very good agreement with simulation results (Fig. 3). The frequency range where tunnelling resonance may occur is directly connected to relative permittivity and the width of the channel. In order to allow tunnelling the channel width and dielectric permittivity should be within a specific range defined by:

$$f_{tun} \cong f_{TE_{10}}^{ch} = \frac{c}{2a_{ch}\sqrt{\varepsilon_{rch}}}, \qquad f_{TE_{10}}^{wg} < f_{tun} < f_{TE_{20}}^{wg} \Rightarrow a_{wg}^2 \varepsilon_{rwg} / 4 \le a_{ch}^2 \varepsilon_{rch} \le a_{wg}^2 \varepsilon_{rwg}. \tag{2}$$

3. Tuning of tunnelling frequency and experimental verification

According to expression (2) the tunnelling frequency is only dependent on the width of the rectangular waveguide and relative dielectric permittivity in the channel, and is fixed for given geometry. In this paper we propose a simple and efficient way of the tuning of tunnelling frequency by means of two short longitudinal slots ($L_s \approx \lambda_0/7$) placed near the very ends of the channel, as can be seen in Fig. 2.

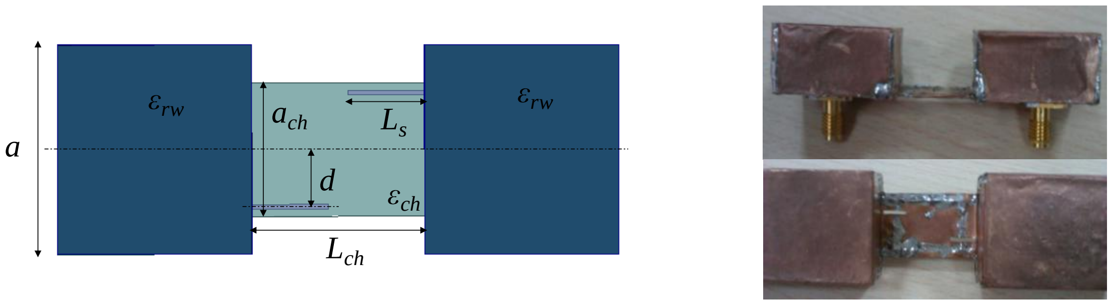

Fig. 2: a) ENZ channel with tuning slots; b) Fabricated ENZ waveguide with coaxial connectors and tuning slots.

The width of the slots is 0.5 mm, and their length and position are varied to examine the optimal values for best sensitivity in frequency tuning. Measured S_{21} and S_{11} parameters are shown in Fig.3. Tunnelling resonance in the case without slots is positioned very close to Fabry-Perot resonance which depends on the distance between coaxial connectors and step discontinuity. When the slots (L_s=6 mm) are introduced, the shift of the tunnelling frequency (Δf=300 MHz) can be observed. Amplitudes of the resonances are lower because of the poor matching of input coaxial connectors, which can be improved by optimizing their length and position. The disagreement between measured and simulated results is mostly due to imprecise width of the channel, which was hand-cut with a knife.

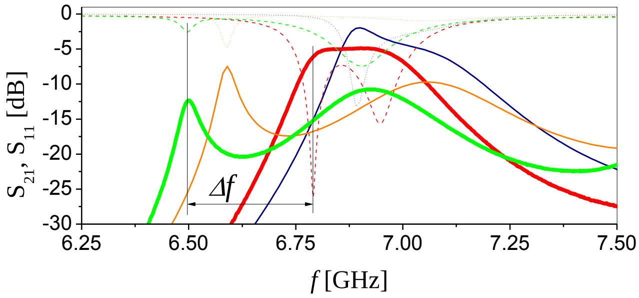

Fig. 3: Simulated results of transmission coefficient (thin full lines) in comparison to experimental results (thick full lines) with corresponding reflection coefficients. Light lines represent the case with introduced slots.

Simulated S_{11} and S_{21} parameters after optimizing the position of the coaxial connectors around the tunnelling frequency are shown in Fig. 4. Slots are placed near the side walls of the channel (d=6 mm offset) and losses in metal cladding and in dielectrics are taken into account. The width of the channel is changed to a_{ch}=14 mm in order to achieve grater tuning scale. It can be seen that the shift of tunnelling frequency is about 17% for the slot with length L_s=8 mm and for the amplitude decrease of 1.5 dB. Maximum achiavable tuning range is about 50% when the channel cut-off frequency is placed close to the cut-off frequency of the first higher mode of input waveguides. Experimental verification of the optimized geometry of the ENZ waveguide is expected in the near future.

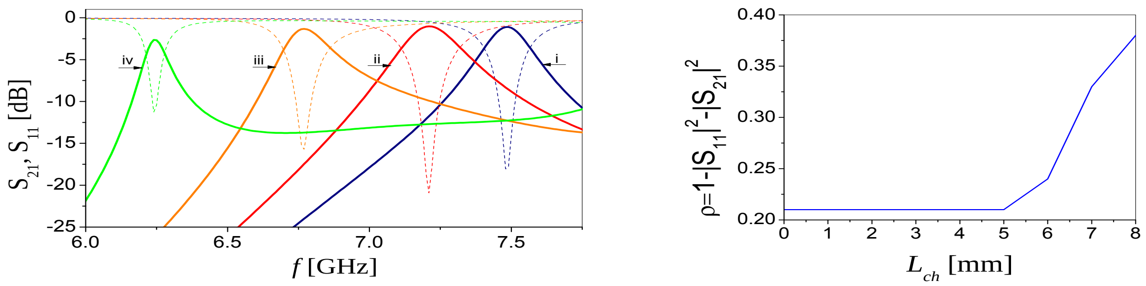

Fig. 4: a) Tunnelling frequency for different slot lengths i) L_s=0 mm, ii) L_s=4 mm, iii) L_s=6 mm, and iv) L_s=8 mm; b) Losses at the tunnelling resonance for different slot lengths.

4. Conclusion

In this paper we have presented a novel design of the ENZ channel, and also a very efficient way of tuning the tunnelling frequency of the channel by means of two longitudinal slots. Experimental results show 300 MHz change in the tunnelling frequency. By optimizing the position and length of coaxial connectors it is possible to obtain wider tuning range (17%) with small decrease of transmission coefficient amplitude (1.5 dB) at the tunnelling frequency.

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