Comparison Between ε-Near-Zero and Fabry-Perot Resonant Transmission Through Waveguide Bends and Channels

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Abstract

Epsilon-Near-Zero (ENZ) materials hold promise for many applications involving fast-wave propagation. One such purpose involves the resonant tunneling through narrow ENZ waveguide channels which may enable unimpeded transmission around bends, abruptions and corners. While Fabry-Perot resonant transmission may provide similar effects for a carefully tuned length at a fixed frequency, this work will show that ENZ thin-channel transmission relies on a different phenomenon and it may provide a more flexible approach, being invariant with the device length, bend angle and bend location.

1. Introduction

While metamaterials have received a lot of attention for their potential applications involving negative index of refraction [1], also of interest are zero index materials, often realized through a vanishingly small permittivity [2-9]. This results in both fast-wave propagation and a characteristically long wavelength. Since abruptions (such as bends and corners) in an ENZ region may become a small fraction of the effective wavelength, basically independent on their actual physical size, they may have a small impact on the waveguide transmission properties. This may provide wire-like qualities to waveguides filled with ENZ materials [8-9].

While not naturally available in the microwave regime, ENZ materials may be realized in several ways. The conventional method is to use subwavelength resonant inclusions. These may be homogenized to yield an effective permittivity [10]. However, resonant inclusions often introduce ohmic and radiation losses associated to material absorption and disorder due to fabrication imperfections. An alternative is to take advantage of the natural wave propagation characteristics of waveguiding structures. For instance, the fundamental mode in the simple rectangular metallic waveguide may be either propagating or evanescent depending on whether the frequency is above or below cut-off frequency, respectively. For TE modes, one could describe the waveguide itself as creating an effective permittivity, which is either positive or negative [11]. However, if the waveguide is precisely at the cut-off frequency of the dominant mode, the wavelength in the direction of propagation stretches out infinitely, yielding ENZ qualities.

It has been shown in our previous works that if a channel filled with an ENZ metamaterial is connecting two larger waveguides supporting propagating modes, one may achieve 100% transmission in the limit of vanishingly small channel height for precisely the frequency for which the channel is at zero permittivity. This occurs with negligible phase difference between the entrance and exit faces of the ENZ region [8-9]. We have also proven this concept experimentally [12].

One may argue that traditional Fabry-Perot resonant transmission possesses many of these same qualities. Indeed, in some respects, ENZ transmission may be regarded as a 0^{th} order Fabry-Perot resonant transmission. However, in many aspects the physics behind this phenomenon is much different. First of all, Fabry-Perot resonant transmission is very sensitive to the channel length. Additionally, the introduction of a bend will result in a localized impedance mismatch, which may inconveniently alter the peak transmission frequency. Such impedance mismatch is much reduced or eliminated if the bend is immersed in an effectively ENZ region, for the reasons discussed above. Additionally, since Fabry-Perot resonant transmission requires a large standing wave within the structure, the bend location with respect to field nulls and maxima may also sensibly affect the location of the transmission peak.

We explore here these issues and elucidate the qualitative differences between thin-channel ENZ transmission and traditional Fabry-Perot resonant transmission.

2. Numerical Results

The results shown in Fig. 1 show the invariance of the ENZ transmission peak with the channel length. In this figure the thick waveguides leading up to and away from the device are made of Teflon ($\varepsilon = 2$) while the thin channel is filled only with air, raising the cutoff frequency. The first peak for each of the two lengths corresponds to ENZ transmission and occurs at the frequency for which the air filled region is at cut-off while the second and remaining peaks are due to Fabry-Perot resonant transmission. Note that the ENZ peak remains at nearly the same frequency in spite of nearly doubling the path length. Additionally, examination of the magnetic field normal to the cutting plane show that the phase difference between entrance and exit planes of the device is almost the same between the two cases, indicating fast-wave propagation.

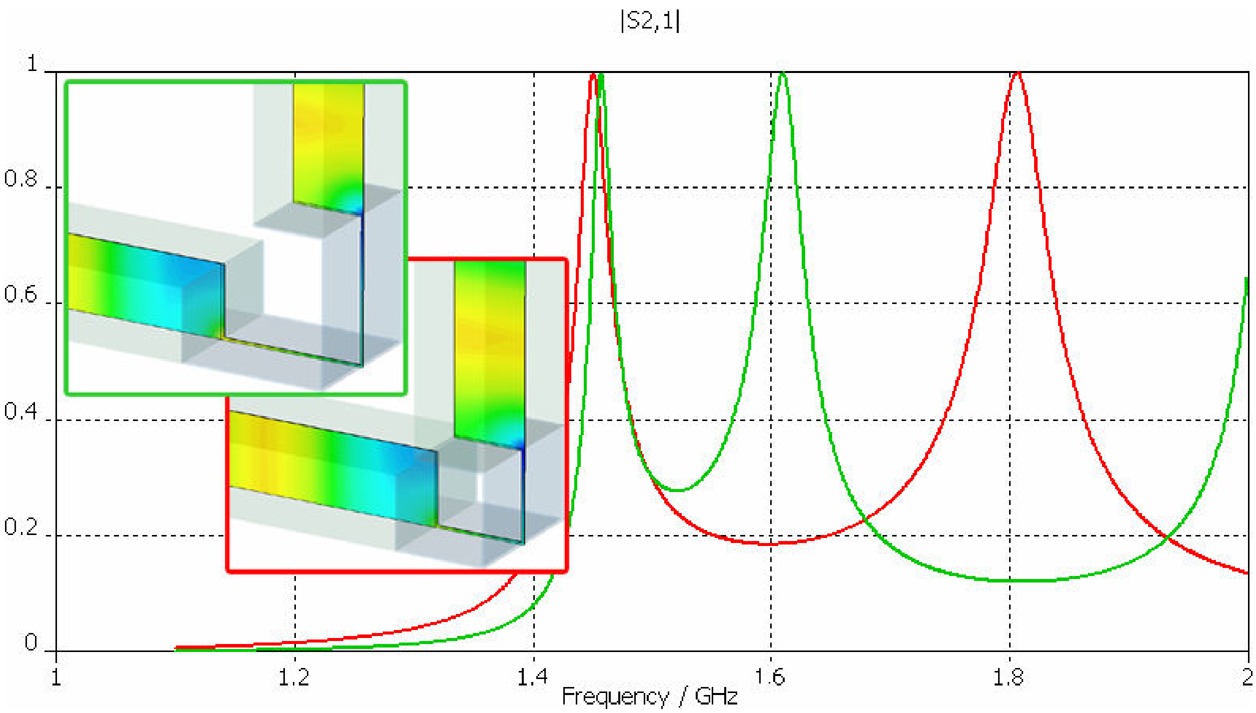

Fig. 1: Transmission for two thin ENZ channel couplers with path lengths of 20.8 cm (green) and 12.7 cm (red). Plot shows the magnitude of the transmission as a function of frequency. Insets show the magnetic field normal to the cut-plane at the center of the structure for each length.

3. References

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