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A Novel Epsilon Near Zero Tunneling Circuit Using Double-Ridge Rectangular Waveguide

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Abstract

In this paper, an epsilon near zero (ENZ) tunneling circuit using a double-ridge rectangular waveguide (RWG) is proposed for the miniaturization of a waveguide component. The proposed ENZ channel and is located in the middle of the input-output RWG (IORWG). The ratio of the height to the width of the channel waveguide is very small compared to the IORWG. By properly adjusting the ridge dimensions, the tunneling frequency of the proposed ENZ channel can be lowered to near the cut-off frequency of the IORWG. For the proposed ENZ tunneling circuit, the approach adopted for extracting the effective permittivity, effective permeability, normalized effective wave impedance, and propagation constant from the simulated scattering parameters was explained. The extracted parameters verified that the proposed channel is an ENZ channel and electromagnetic energy is tunneling through the channel. Simulation and measurement results of the fabricated ENZ channel structure agreed.

Key Words: Double Ridge, Epsilon Near Zero, Rectangular Waveguide, Tunneling.

Ⅰ. Introduction

Metamaterials, which have been of interest in the fields of physics and engineering for the past several years, are artificial composite materials with negative indexes of permittivity or permeability. Recently, metamaterials with epsilon near zero (ENZ) have been investigated for interesting phenomena, such as supercoupling, transparency, cloaking devices, and highly directive antennas at microwave and optical frequencies [1–3]. The rapid growth and significant attention paid to ENZ materials is because of their ability to achieve a very long wavelength, allowing for the propagation of a "static-like" character of the electromagnetic field.

Silveirinha and Engheta [4] investigated the theory of supercoupling, squeezing wave energy, and field confinement in narrow channels and tight bends using ENZ materials. Previous studies [5, 6] have experimentally demonstrated ENZ materials that exhibit supercoupling and energy squeezing using a microwave waveguide. These effects can be applied to a waveguide bend, an antenna matching circuit, a microwave filter, and a dielectric sensing application [1, 7–9]. These technologies have a potential advantage for miniaturization because the electromagnetic energy is tunneled at the specific frequency through a narrow waveguide regardless of the total length of the ENZ channel. Radiation loss can be reduced, as compared with other metamaterials, because these technologies are based on a microstrip and waveguide shape. The tunneling frequency is near the cut-off frequency of the dominant mode in the waveguide. In order to minimize the size of a waveguide device, an ENZ channel can

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be used by a double-ridge rectangular waveguide (RWG) that has a lower cut-off frequency, instead of a general RWG [10, 11].

In this paper, we introduce an ENZ tunneling circuit using a double-ridge RWG and we explain the structure of the proposed ENZ channel. The cut-off frequency of the double-ridge RWGs, including a general RWG, is calculated. For the ENZ tunneling circuit using a RWG and a double-ridge RWG, scattering parameters were obtained using the commercial finite element method simulator, Ansoft high-frequency structure simulator (HFSS) software [12]. We discuss in detail two types of transmission resonance phenomena, such as zeroth-order resonance (ZOR) and Fabry-Perot (FP) resonance, from the results obtained in the simulations. We also explain the approach adopted for extracting the constitutive parameters (effective permittivity, permeability, wave impedance, and propagation constant) of the ENZ channel from the scattering parameters using the retrieval method based on an RWG [13].

Using the extracted constitutive parameters, we explain that the proposed ENZ tunneling circuit using a double-ridge RWG is an ENZ channel, and we discuss, in terms of impedance matching, what electromagnetic energy is tunneled at the tunneling frequency. The measured results of the fabricated ENZ tunneling circuit were quite similar to simulated results, with tunneling frequencies being 9.169 GHz (simulated) and 9.172 GHz (measured).

II. Structure of the Proposed ENZ Tunneling Circuit and the Resonance Properties

1. *Description of the Structure of the Proposed ENZ Channel*

Fig. 1 shows the geometrical structure of the proposed ENZ tunneling circuit, where the ENZ channel is centrally located in the input-output RWG (IORWG, WR-90) with a cross section of $a \times b$ (mm^2). The ENZ channel is composed of a double-ridge RWG with a ridge width w_r and a ridge gap h_g in a rectangular waveguide $w_c \times h_c$ (mm^2). The length of the proposed ENZ channel is d.

The ratio of the height of the IORWG to that of the proposed ENZ channel is very high, given as follows:

$$\frac{b}{h_c} >> 1 \qquad (1)$$

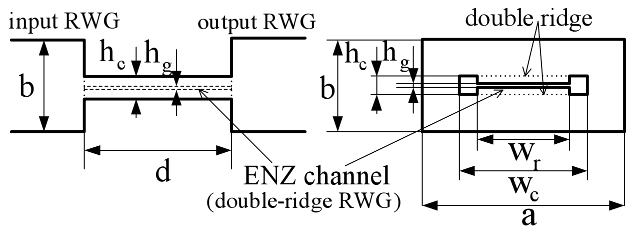

Fig. 1. Geometrical parameters of the proposed epsilon near zero (ENZ) tunneling circuit. (a) Lateral side view and (b) cross-sectional view. RWG = rectangular waveguide.

Compared to RWGs, ridge waveguides [10, 11] have the advantages of a wide fundamental-mode operation bandwidth, a low cut-off frequency, and low wave impedance. In the ENZ channel, the cut-off frequencies of the RWG and the double-ridge RWG are as follows:

$$f_{cr} = \frac{c_0}{2w_c} \qquad (2)$$

$$f_{cd} = \frac{c_0}{2}\frac{1}{w_c - w_r}\left[1 + A + B\right]^{-\frac{1}{2}} \qquad (3)$$

with

$$A = \frac{4}{\pi}\left\{\left(1 + 0.2\sqrt{\frac{h_c}{w_c - w_r}}\right)\cdot\frac{h_c}{w_c - w_r}\ln \operatorname{cosec}\left(\frac{\pi h_g}{2h_c}\right)\right\} \qquad (4)$$

and

$$B = \left(2.45 + 0.2\frac{w_r}{w_c}\right)\cdot\frac{w_r h_c}{(w_c - w_r)h_g} \qquad (5)$$

where c_0 is the speed of light in free-space, and ln is the natural logarithm. As mentioned in Eq. (2), the cut-off wavelength of an RWG is equal to twice the waveguide width w_c. We can estimate the cut-off frequency of the double-ridge RWG in Eq. (3). To calculate accurately the cut-off frequency of the double-ridge waveguide, the transverse resonance method (TRM) is used [14]. As seen in Fig. 2, the cut-off frequency is obtained by using the TRM under the initial value of the approximated cut-off frequency from Eq. (3).

The cut-off frequency of the ENZ channel without the double-ridge is 10.338 GHz. As the gap of the ridge h_g de-

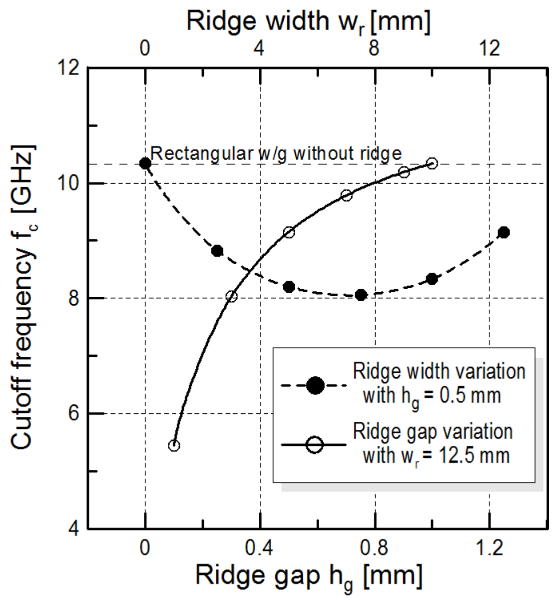

Fig. 2. Cut-off frequency against ridge variation (w_c = 14.5 mm, h_g = 1 mm).

creases to 0.1 mm and the width of the ridge w_r is maintained at 12.5 mm, the cut-off frequency of the ENZ channel decreases to 5.446 GHz. This indicates that the cut-off frequency becomes low and returns to high when the width of the ridge w_r increases to 12.5 mm, keeping the gap of the ridge h_g equal to 0.5 mm. Consequently, because the cut-off frequency of the ENZ channel is reduced to less than the cut-off frequency of the IORWG at 6.557 GHz, we can appropriately change the structure of the ridge according to the purposes of the ENZ channel.

The guide wavelength λ_g, propagation constant k_g, phase velocity v_p, and the characteristic impedance Z_r in the ENZ channel are given as follows [14, 15]:

$$\lambda_g = \frac{\lambda_0}{\sqrt{1-\left(\frac{\lambda_0}{\lambda_c}\right)^2}} \tag{6}$$

$$k_g = 2\pi / \lambda_g \tag{7}$$

$$v_p = f\lambda_g = 2\pi f / k_g \tag{8}$$

$$Z_r = Z_r(\infty)\cdot(\lambda_g / \lambda_0) \tag{9}$$

where λ_0 is the wavelength in free space, λ_c is the cut-off wavelength of a waveguide, and $Z_r(\infty)$ is the characteristic impedance of the ENZ channel at infinite frequency. At the cut-off frequency $\lambda_c = \lambda_0$, the guide wavelength is infinite, and the guide wavenumber is zero. This suggests that the electromagnetic fields remain almost unchanged along the longitudinal direction because they are similar to the static electromagnetic fields. Because the characteristic impedance of the ENZ channel is significantly increased around the cut-off frequency, the characteristic impedance of the ENZ channel is equal to the characteristic impedance of the IORWG. This implies that tunneling phenomena are observed to occur when two characteristic impedances are equal. The tunneling frequency is near the cut-off frequency of the ENZ channel.

2. Scattering Parameters and Extraction of Constitutive Parameters

Let us consider the reflection and transmission properties of the ENZ channel using an RWG and a double-ridge RWG. First, to obtain scattering parameters, the ENZ channel using an RWG at an operating frequency of 10.370 GHz was created to test tunneling phenomena with a full-wave simulator, based on the finite element method, Ansoft HFSS. The results were processed by de-embedding from each port of the IORWG to the interfaces of the ENZ channel. The IORWG uses a standard WR-90 RWG. Table 1 lists the dimensions of the standard RWG and the proposed ENZ channel waveguide applied to a resonator of near-field microwave microscopy. The cut-off frequency f_{cr} and the cut-off wavelength λ_{cr} of this ENZ channel are 10.338 GHz

Table 1. Dimensions of the proposed epsilon near zero (ENZ) channel waveguide

Parameter	Value	Parameter	Value
a	22.86 mm	w_r	12.5 mm
b	10.16 mm	h_g	0.5 mm
w_c	14.5 mm	d	40 mm
h_c	1.0 mm	-	-

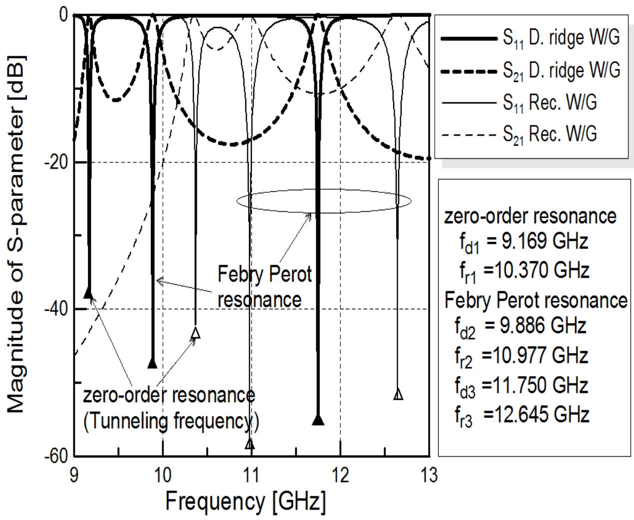

Fig. 3. Simulation results of the proposed epsilon near zero (ENZ) channel. W/G = waveguide.

and 29.0 mm, respectively. To reduce the tunneling frequency in the rectangular waveguide, a double-ridge RWG was used, as shown in Fig. 1. Fig. 3 shows the simulation results of the ENZ channel using the RWG and the double-ridge RWG for a frequency range of 9.0 to 13.0 GHz. These results imply that the two types of transmission resonances, ZOR and FP, have been observed in the proposed ENZ channel. The tunneling frequency of the ENZ channel using the RWG and the double-ridge RWG are 10.370 and 9.169 GHz, respectively.

Because the frequencies are near the cut-off frequency of each ENZ channel (10.336 and 9.152 GHz), the guide propagation constant is close to zero, implying that the length of the ENZ channel is insensitive because the guide wavelength is very long. These resonances are of the ZOR type. The ZOR mainly depends on the transverse cross-sectional shape, which is related to the cut-off frequency of an ENZ channel. Other resonant frequencies of the ENZ channel using the RWG and the double-ridge RWG are (f_{r2} = 10.977 GHz, f_{r3} = 12.645 GHz) and (f_{d2} = 9.886 GHz, f_{d3} = 11.750 GHz). These resonances are of the FP resonance type. The FP resonances occur when the length of the ENZ channel is around an integer number of the half-guide wave length, $n\frac{\lambda_g}{2}$ (n = 1, 2, 3, ...). The wavelengths of the channel using the RWG and the double-ridge RWG are 81.2

mm (at f_{r2} = 10.977 GHz) and 80.2 mm (at f_{d2} = 9.886 GHz), respectively. The length of the proposed ENZ channel d is 40 mm. The length of the ENZ channel at the resonance frequencies does not exactly agree with $n\frac{\lambda_g}{2}$, because of the shunt susceptance for the stored electromagnetic energy at the interface of the IORWG and the ENZ channel.

The effective permittivity ε_{eff}, permeability μ_{eff}, wave impedance Z_{eff}, and propagation constant γ_{gd} can be extracted using the retrieval method from the simulated scattering parameters [13, 16]. The scattering parameters can be expressed as functions of the reflection coefficient Γ and the transmission coefficient T as follows:

$$S_{11} = \frac{\Gamma(1-T^2)}{1-\Gamma^2 T^2}, \tag{10}$$

$$S_{21} = \frac{T(1-\Gamma^2)}{1-\Gamma^2 T^2}. \tag{11}$$

Eqs. (10) and (11) can be solved for

$$\Gamma = K \pm \sqrt{K^2 - 1} \tag{12}$$

with

$$K = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}} \tag{13}$$

and

$$T = \frac{S_{11} + S_{21} - \Gamma}{1-(S_{11}+S_{21})\Gamma}. \tag{14}$$

In Eq. (12), the sign of the square root has to be chosen such that $|\Gamma| \leq 1$. The propagation constants γ_{gr} and γ_{gd} of the IORWG and the ENZ channel using the double-ridge RWG can be calculated as follows:

$$\gamma_{gr} = j2\pi\sqrt{\frac{1}{\lambda_0^2} - \frac{1}{\lambda_{cr}^2}} \tag{15}$$

$$\gamma_{gd} = [\ln(1/T)]/d \tag{16}$$

where λ_{cr} is the cut-off wavelength of the IORWG. The effective permittivity ε_{eff} and permeability μ_{eff} can be determined using Eqs. (12), (15), and (16) as follows:

$$\varepsilon_{eff} = \frac{\gamma_{gd}(1-\Gamma)}{\lambda_{gr}(1+\Gamma)}, \tag{17}$$

$$\mu_{eff} = \frac{\gamma_{gd}(1-\Gamma)}{\lambda_{gr}(1+\Gamma)}. \tag{18}$$

The effective wave impedance of the ENZ channel is

$$Z_{eff} = Z_{0r}\sqrt{\frac{\mu_{eff}}{\varepsilon_{eff}}} = Z_{0r}\frac{(1+\Gamma)}{(1-\Gamma)}, \tag{19}$$

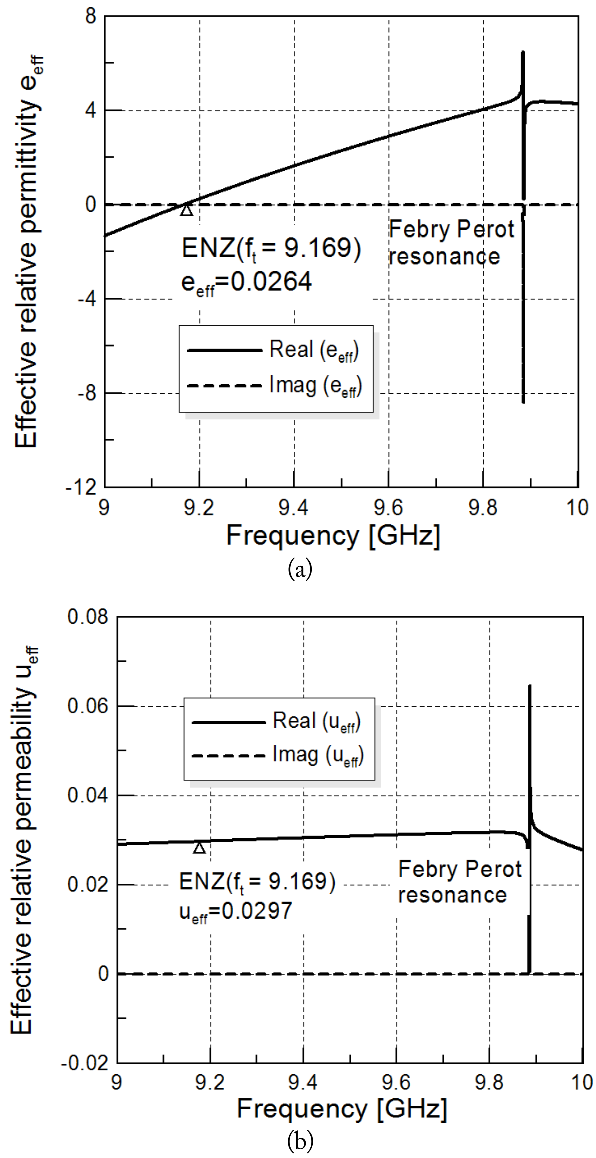

Fig. 4. Effective permittivity and permeability for the proposed epsilon near zero (ENZ) channel. (a) Effective permittivity ε_{eff} and (b) effective permeability μ_{eff}.

where Z_{0r} is the wave impedance of the IORWG. Then from Eqs. (19) and (16), the reflection coefficient and transmission coefficient are finally determined as

$$\Gamma = \frac{Z_{eff} - Z_{0r}}{Z_{eff} + Z_{0r}} \tag{20}$$

and

$$T = e^{-\gamma_{gd} d}. \tag{21}$$

At the tunneling frequency $Z_{eff} = Z_{0r}$, the reflection coefficient and transmission coefficient have to be "0" and "1", respectively.

The extracted effective permittivity ε_{eff}, permeability μ_{eff}, normalized wave impedance z_{eff}, and propagation constant γ_{gd} are shown in Figs. 4 and 5.

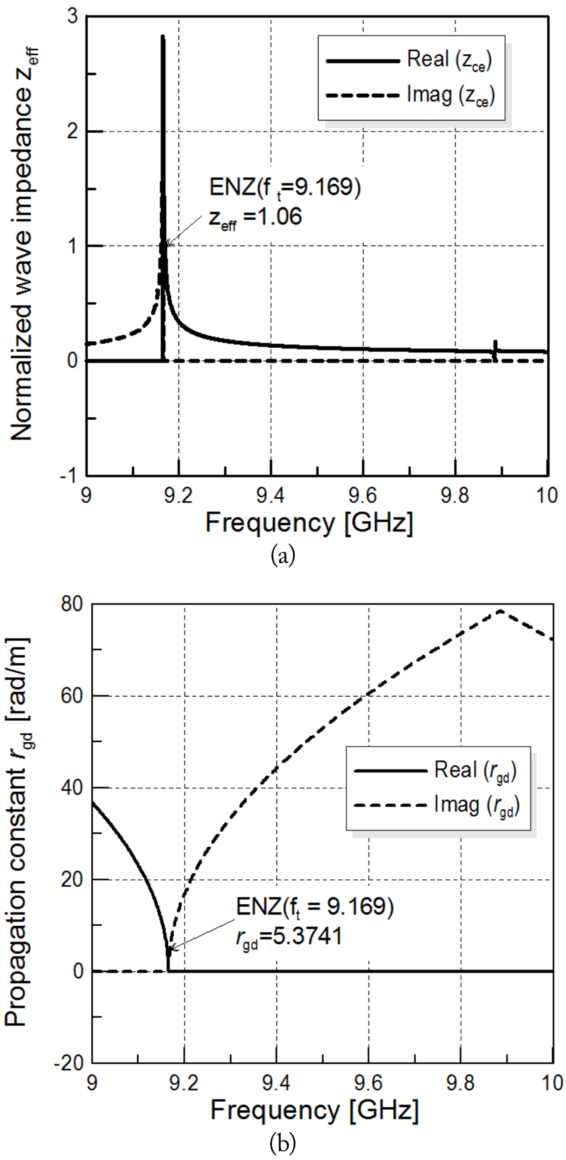

Fig. 5. Normalized wave impedance z_{eff} and propagation constant γ_{gd}. ENZ = epsilon near zero.

In Fig. 4(a), we note that the proposed structure is the ENZ channel, because the real value of the effective permittivity ε_{eff} is 0.0264 at the tunneling frequency (9.169 GHz). The real value of the effective permeability is 0.0297 in Fig. 4(b). The normalized wave impedance z_{eff}, which is normalized with the wave impedance Z_{0r} of the IORWG, is 1.06 in Fig. 5(a). The effective wave impedance of the proposed ENZ channel using the double-ridge RWG is typically lower than that of the IORWG, but that of the former was significantly increased around the cut-off frequency. Then, the effective wave impedance was equal to the wave impedance of the IORWG at the tunneling frequency. Thus, good impedance matching was observed, as with [17], implying that the tunneling phenomena of electromagnetic energy occurred in the ENZ channel. The propagation constant γ_{gd} of the ENZ channel as shown in Fig. 4(b) is zero at the cut-off

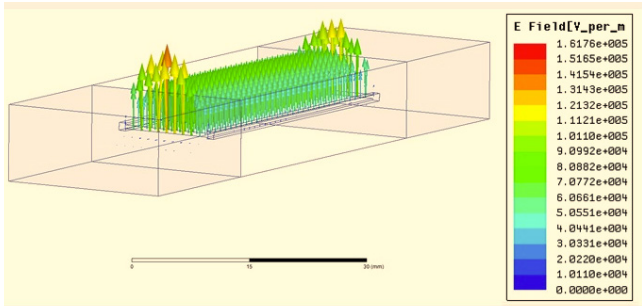

Fig. 6. Electric field distribution along the proposed epsilon near zero (ENZ) channel.

frequency of 5.3741 (rad/m) and the guide wavelength is 1.1691 m at the tunneling frequency (9.169 GHz). The phase variation in the electric fields in the ENZ channel using a double-ridge waveguide is approximately 0.2150 rad (12.3186°). It is clear that the effective permittivity has a value of zero near the tunneling frequency, and the propagation constant is near zero, which satisfies the conditions for ENZ behavior.

Fig. 6 shows the field distribution along the channel at the tunneling frequency, which exhibits little phase shift along the channel.

Ⅲ. Fabrication and Measurements of the ENZ Channel

Aluminum was used for the ENZ channel circuit. The ENZ channel using the double-ridge RWG was manufactured using a wire electro-discharge machine, as shown in Fig. 7. The IORWGs, which were the size of a WR-90 standard waveguide, were connected to the ENZ channel using separated screws. The ENZ tunneling circuit for characteristic measurements was connected to a network analyzer (Anritsu 37397C) through a coaxial waveguide adapter, which differs from the waveguide port used in the simulation to compute the input reflection coefficient (S_{11}).

This causes small differences between the measured and simulated input reflection coefficients, as shown in Fig. 8. The measured tunneling frequency f_m is 9.172 GHz and has a tolerance of 3 MHz in comparison with the theoretical value (f_{d1} = 9.169 GHz).

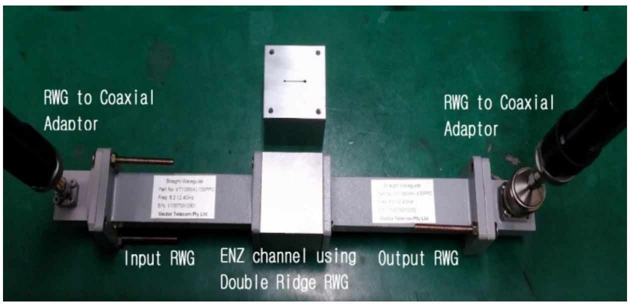

Fig. 7. Photo of the fabricated epsilon near zero (ENZ) channel using the double-ridge rectangular waveguide (RWG).

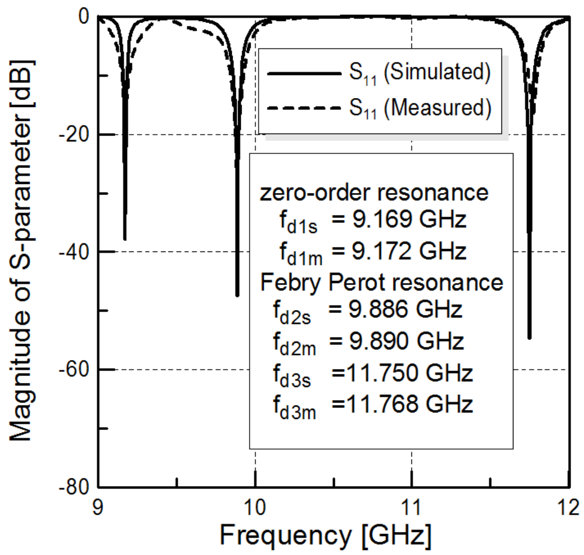

Fig. 8. Simulated and measured scattering parameters (S_{11}) of the proposed epsilon near zero (ENZ) tunneling circuit using a double-ridge rectangular waveguide.

IV. Conclusions

In this paper, we proposed an ENZ tunneling circuit using a double-ridge waveguide for the miniaturization and field confinement of waveguide circuits and the characteristics of that system were analyzed. The proposed ENZ channel which was centrally located in a standard RWG, used a narrowed double-ridge RWG. The tunneling frequency of the proposed ENZ channel can be reduced to near the cut-off frequency of the IORWG. From the extracted parameters, the proposed double-ridge waveguide channel must become the ENZ channel because the effective permittivity is zero at the cut-off frequency and close to zero at the tunneling frequency. The normalized effective wave impedance is almost "1" at the tunneling frequency, implying that we have verified that the electromagnetic energy was tunneled. The measured scattering parameters of the proposed ENZ channel agreed with the simulation results, which had tunneling frequencies of 9.169 GHz (simulated) and 9.172 GHz (measured). In the future, we will apply an ENZ channel using a double-ridge waveguide to the probe antenna of a near-field microwave microscope.

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