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Frequency Range Dependent TE$_{10}$ to TE$_{40}$ Metallic Waveguide Mode Converter

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ABSTRACT

Dielectric rod arrays in a metallic waveguide alter the propagation modes and group velocities of electromagnetic waves. We focus on TE$_{10}$-to-TE$_{20}$ mode converters and investigate the variation in their behavior with frequency. In this investigation, a mode converter is proposed that passes the TE$_{10}$ mode at frequencies lower than 2f$_c$, and converts the TE$_{10}$ mode into the TE$_{40}$ mode for frequencies higher than 2f$_c$, which is achieved by a combination of TE$_{10}$-TE$_{20}$ mode converters.

Keywords: *Metallic Waveguide, Dielectric Rod, Mode Converter*

1. Introduction

Metallic waveguides have major advantages, such as low propagation loss and high power transmission in the microwave frequency range. However, one disadvantage is that the usable frequency range is restricted to $f_c < f < 2f_c$, because the TE$_{20}$ mode is possible in the frequency region higher than $2f_c$ for rectangular metallic waveguides. A ridge waveguide [1] (or double-ridge waveguide) has an advantage in that it can spread the propagating frequency range as a result of reduction in the cutoff frequency for the TE$_{10}$ mode. However, one disadvantage is that the construction of the waveguide structure is complex.

Power sources, such as watt-class impact ionization avalanche transit-time (IMPATT) diodes or Gunn diodes, are readily available and for high frequency use, these power sources are sometimes combined due to their low power rating. Power dividers and power combiners may be easily set up using mode converters. For example, a TE$_{10}$-TE$_{30}$ mode converter easily offers a three-port power divider, and a three-way power combiner can be arranged by reversal. A power combiner is useful for application to Gunn diodes in a waveguide array [2], because it converts the TE$_{30}$ mode to the TE$_{10}$ mode.

2. Frequency Range Dependent TE$_{10}$ to TE$_{20}$ Mode Converter

We have reported a mode converter that passes the TE$_{10}$

mode at low frequencies and converts the TE$_{10}$ mode into the TE$_{20}$ mode at high frequencies [3]. The reflection of the TE$_{20}$ mode, however, is not small enough because an asymmetrical arrangement increases the reflection of the TE$_{20}$ mode. In this investigation, a new mode converter is proposed that passes the TE$_{10}$ mode at low frequencies and efficiently converts the TE$_{10}$ mode into the TE$_{40}$ mode at high frequencies. The structure contains the proposed TE$_{10}$-TE$_{20}$ mode converters.

Figure 1 shows the frequency eigenvalues of a conventional metallic waveguide for a given k wave vector. In this figure, the wave vector k and frequency ω are normalized by the waveguide width w. The waveguide allows propagation of only the TE$_{10}$ mode for $0.5 < \omega w/2\pi c < 1$, and only the TE$_{10}$ and TE$_{20}$ modes for $1 < \omega w/2\pi c < 1.5$. If the TE$_{10}$ mode is converted into the TE$_{20}$ mode, the group velocity A of TE$_{10}$ must change to the group velocity B of TE$_{20}$ for $1 < \omega w/2\pi c$. However, the group velocity C is not changed for $0.5 < \omega w/2\pi c < 1$, because it remains in the TE$_{10}$ mode.

A metallic waveguide that contains in-line dielectric rods can allow propagation of single modes in two frequency regions [4]. For example, **Figure 2** shows the eigenvalues of a waveguide in which dielectric rods are periodically positioned along the central axis of the waveguide. The dielectric constant of the rods is assumed to be $\varepsilon_r = 24$ and their radius is $r = 0.064a$ (where a represents the spatial period of the dielectric array). The propagation modes in a waveguide with in-line dielectric
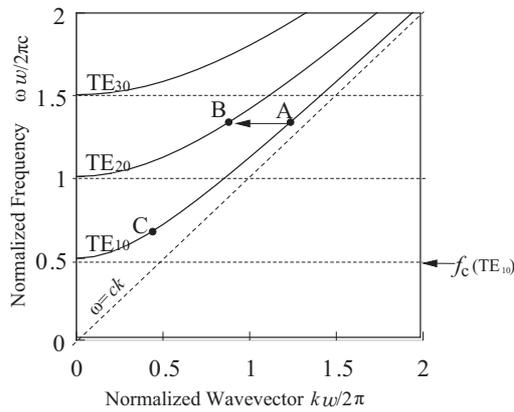
Figure 1. Frequency eigenvalues of a conventional metallic waveguide for a given wave vector *k*.
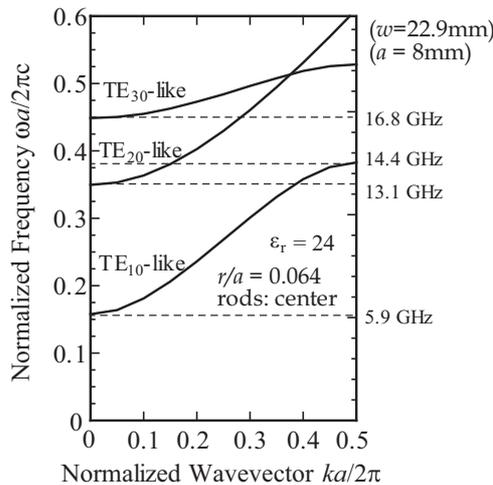
Figure 2. Frequency eigenvalues of a waveguide in which dielectric rods are placed periodically along the central axis. The dielectric constant of a rod is assumed to be $\varepsilon_r = 24$ and the radius is assumed to be $r = 0.064a$.

rods of period *a* are calculated using a supercell approach [5] by applying appropriate periodic Bloch conditions at the boundary of the unit cell [6,7]. In **Figure 2**, if $a = 8$ mm and $w = 22.9$ mm (WR-90 waveguide), then the electromagnetic wave propagates in a single mode for 5.9 - 13.1 GHz (TE_{10}-like mode) and 14.4 - 16.8 GHz (TE_{20}-like mode).

If the transverse electromagnetic field distribution is gradually changed from TE_{10} to TE_{20} and the group velocity A is gradually changed to B, then reflection may be reduced for $1 < \omega w/2\pi c$. However, if the group velocity C is not significantly changed, reflection may be suppressed for $0.5 < \omega w/2\pi c < 1$. The mode profile gradually shifts from TE_{10} to TE_{20}; therefore, the position of the dielectric rods is changed from near the sidewall of the waveguide to the center, as shown in **Figure 3**. The
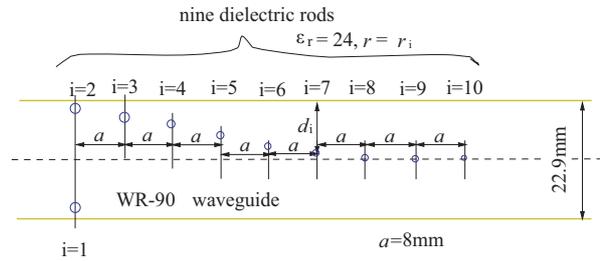
Figure 3. Proposed structure of the TE_{10}-to-TE_{20} mode converter.

first rod ($i = 1$) is located at the opposite side of the second rod ($i = 2$), because a symmetrical arrangement will decrease the reflection of the TE_{20} mode.

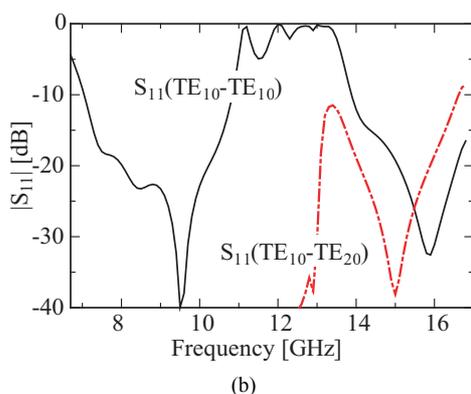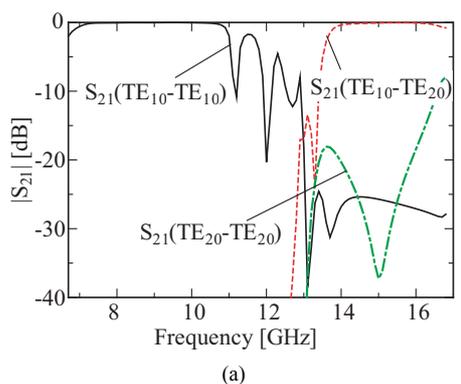The group velocity is given by $v_g = \dfrac{1}{(dk/d\omega)}$; however, the group velocity for the waveguide depicted in **Figure 3** cannot be determined easily. When the position of the dielectric rods is fixed to *d*, the group velocity v_g in the first band is changed by variation of the radius *r*. However, the group velocity in the second band is simultaneously changed; thus, the two group velocities cannot be changed independently.

If the group velocity is normalized using the velocity of light in a vacuum c_0, then v_g/c_0 will be the same as the gradient of the characteristic curve. Therefore, when *d* and *r* are fixed to specific values, v_g/c_0 can be calculated for the periodic structure of dielectric rods at a specific frequency. If group velocity A is gradually changed to B for $1 < \omega w/2\pi c$ while *d* is varied and group velocity C is not changed for $0.5 < \omega w/2\pi c < 1$, then one unit of each pair of *d* and *r* connects to its respective pair to form the structure shown in **Figure 3**.

The metallic waveguide width is assumed to be $w = 22.9$ mm, (WR-90; $f_c \approx 6.55$ GHz), and the period a is fixed at 8 mm. **Figure 4** shows a sample of the calculated normalized velocity along the waveguide axis at 8 and 16 GHz for dielectric rods (LaAlO₃: $\varepsilon_r = 24$; radius *r* [mm]) aligned at a distance *d* [mm] from the sidewall. It is desirable that the normalized velocity A (TE_{10}: $v_g/c_0 = 0.912$) decreases monotonically to B (TE_{20}: $v_g/c_0 = 0.574$) at 16 GHz and the normalized velocity C (TE_{10}: $v_g/c_0 = 0.574$) is not changed at 8 GHz. However, at 16 GHz, this condition is not satisfied near $d = 10$ mm, because a dielectric rod is located at the point where the electric field is a minimum. On the other hand, if the dielectric rod is placed near the sidewall of the waveguide, it will be located at the point where the electric field is a maximum. The characteristics are complex in the transition region (near $d = 10$ mm). The waveguide must be designed so as not to vary the group velocity at 8 GHz. After calculating v_g for pairs of d_i and r_i, if group velocity A
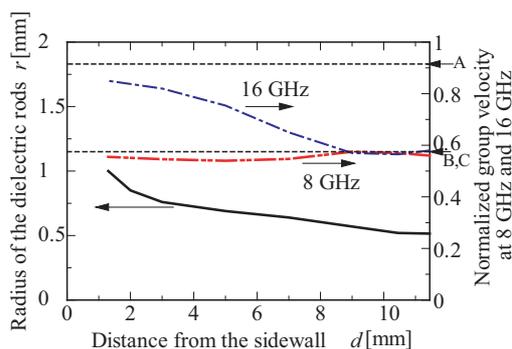
Figure 4. Group velocity (dotted lines) in a metallic waveguide containing a periodic array of dielectric rods for various distances d, location of the rods, and corresponding radii r_i (solid line) of the rods, at 8 and 16 GHz.
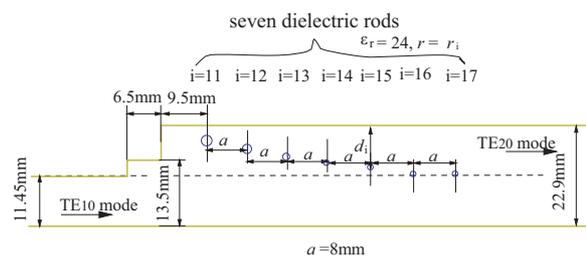
Table 1. Location and radius of the dielectric rods.

Rod Number i	Distance d_i from the Sidewall [mm]	Radius r_i of the dielectric rod [mm]
1	21.6	0.85
2	1.3	0.9
3	3	0.76
4 and 11	5	0.69
5 amd 12	7	0.64
6 and 13	9	0.57
7 and 14	10.45	0.52
8 and 15	11.45	0.515
9 and 16	11.45	0.515
10 and 17	11.45	0.36

(a)

(b)

Figure 5. S parameters for the TE$_{10}$-to-TE$_{20}$ mode converter. (a) |S$_{21}$|, and (b) |S$_{11}$|.

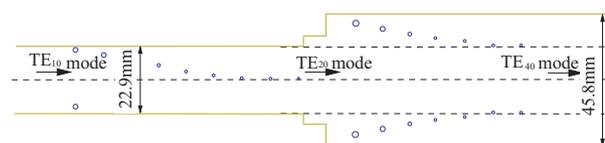is gradually changed to B, then each pair of d_i and r_i are combined (see **Figure 3**).

The last rod ($i = 10$) has $r_1 = 0.36$ mm and the remainder have a cross-sectional radius of 0.515 mm to reduce electromagnetic reflection at low frequencies. Ten dielectric rods are placed from near the sidewall to the center with decreasing rod radius r_i and with constant a (=8 mm). **Table 1** shows the relation between the distance di and radius r_i. The S parameters between the input port

**Figure 6. Structure of the proposed TE$_{10}$-to-TE$_{20}$ mode converter.**

Figure 7. Structure of the proposed TE$_{10}$-to-TE$_{40}$ mode converter.

(port 1) and output port (port 2) were calculated using HFSS software by Ansoft [8], and the results are shown in **Figures 5(a)** and **(b)**. Electromagnetic waves propagate as the TE$_{10}$ mode for 7.2 - 10.7 GHz and the TE$_{10}$ mode is converted into the TE$_{20}$ mode for 14.2 - 16.4 GHz at an efficiency of over 95%.

3. Frequency Range Dependent TE$_{10}$ to TE$_{40}$ Mode Converter

A TE$_{10}$ to TE$_{40}$ mode converter can be considered by combination of TE$_{10}$ to TE$_{20}$ mode converters. Another structure of the TE$_{10}$-to-TE$_{20}$ mode converter is proposed and is shown in **Figure 6**. The locations of the dielectric rods are indicated in **Table 1**. The structure of the proposed TE$_{10}$-to-TE$_{40}$ mode converter, which is composed of three TE$_{10}$-to-TE$_{20}$ mode converters, is shown in **Fig-**

(a)

(b)

(c)
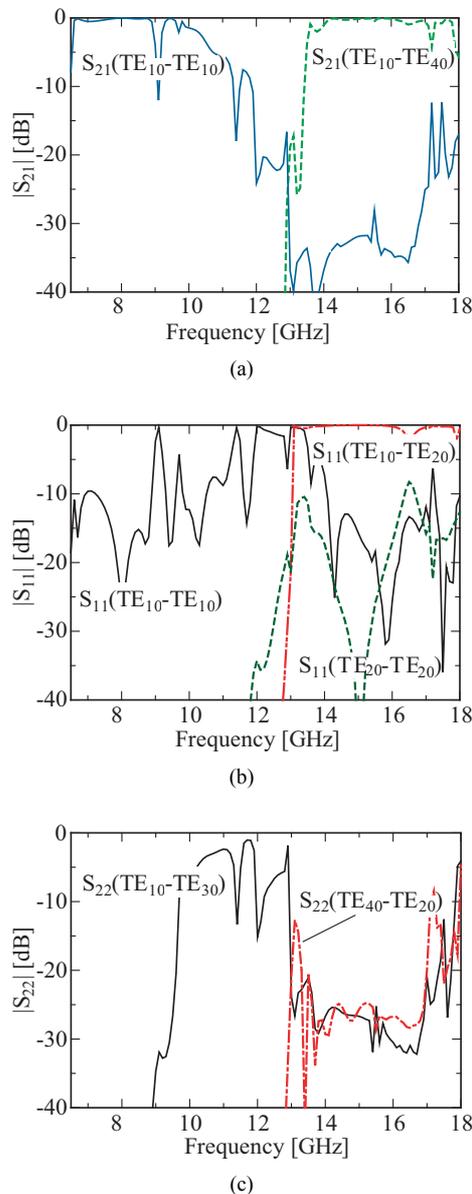
Figure 8. S parameters for the TE$_{10}$-to-TE$_{40}$ mode converter. (a) |S$_{21}$|, (b) |S$_{11}$|, and (c) |S$_{22}$|.

ure 7. The S parameters between the input port (port 1) and output port (port 2) calculated using HFSS are shown in **Figures 8(a)**, **(b)** and **(c)**.

4. Conclusions

We have previously reported that single-mode propaga-

tion is possible in a metallic waveguide with dielectric rod arrays along its central axis using the TE$_{10}$ and TE$_{20}$ modes. A new mode converter is proposed that propagates the TE$_{10}$ mode at low frequencies and converts the TE$_{10}$ mode into the TE$_{40}$ mode at high frequencies by slight variation of the group velocity. It was shown that electromagnetic waves propagate as the TE$_{10}$ mode around 8 GHz and that the TE$_{40}$ mode is converted into the TE$_{10}$ mode around 16 GHz.

5. Acknowledgements

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