

# Waveguide Mode Converters

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## 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<sub>20</sub> mode is possible in a frequency region higher than  $2f_c$  for rectangular metallic waveguides. A ridge waveguide (Cohn, 1947) (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<sub>10</sub> mode. However, one disadvantage is that the attenuation constant becomes large.

Power sources, such as watt class IMPATT diodes or Gunn diodes, are readily available, and for high frequency use, power sources are sometimes combined, due to their low power rating. However, power combiners consisting of cavity resonators usually have narrow bandwidths (For example, Matsumura et al., 1987). Power dividers and power combiners may be easily setup using mode converters. For example, a TE<sub>10</sub>–TE<sub>30</sub> mode converter easily offers a three-port power divider, and a three-way power combiner can be composed by reversal. A power combiner is useful for application to Gunn diodes in a waveguide array (Bae et al., 2000), because it converts the TE<sub>30</sub> mode to the TE<sub>10</sub> mode.

## 2. Design method of the mode converters

We have reported that single-mode propagation is available for a metallic waveguide with dielectric rods arrayed at the center of the waveguide in the frequency under twice the cutoff frequency region using the TE<sub>10</sub> mode, and in the frequency over twice the cutoff frequency region using the TE<sub>20</sub> mode, because of restrictions of the TE<sub>10</sub> mode (Kokubo, 2007; Kokubo & Kawai, 2009). However, a TE<sub>20</sub>-like mode, which is propagated in the second band, is an odd mode, and generation systems for odd modes have seldom been reported. In this investigation, a mode converter is proposed which passes through the TE<sub>10</sub> mode for the low frequency range and efficiently converts TE<sub>10</sub> to TE<sub>20</sub> mode for the high frequency range.

### 2.1 Design method of the TE<sub>10</sub>-to-TE<sub>20</sub> mode converter

The frequency eigenvalues of a conventional metallic waveguide in a given  $k$  wavevector are shown in Fig. 1. In this figure, the wavevector  $k$  and frequency  $\omega$  are normalized using the width of the waveguide  $w$ . The electromagnetic wave propagates the TE<sub>10</sub> mode only for  $0.5 < \omega w / 2\pi c < 1$ , and can propagate TE<sub>10</sub> and TE<sub>20</sub> modes for  $1 < \omega w / 2\pi c < 1.5$ . If these two

modes are excited by only the  $TE_{10}$  mode, the group velocity of  $TE_{10}$  (A) must be changed to that of  $TE_{20}$  (B) for  $1 < \omega w / 2\pi c < 1.5$ . On the other hand, the group velocity (C) is not changed for  $0.5 < \omega w / 2\pi c < 1$ , because this remains in the  $TE_{10}$  mode. If the distribution of the transverse electromagnetic field is gradually changed from  $TE_{10}$  to  $TE_{20}$ , and group velocity (A) is also gradually changed to (B), then the reflection may be reduced for  $1 < \omega w / 2\pi c < 1.5$ . On the other hand, if the group velocity (C) is not significantly changed, the reflection may also be suppressed for  $0.5 < \omega w / 2\pi c < 1$ . Since the mode profile gradually shifts from  $TE_{10}$  to  $TE_{20}$ , the dielectric rods are replaced from near the sidewall to the center of the waveguide. In other words, the basic setup is shown in Fig. 2.

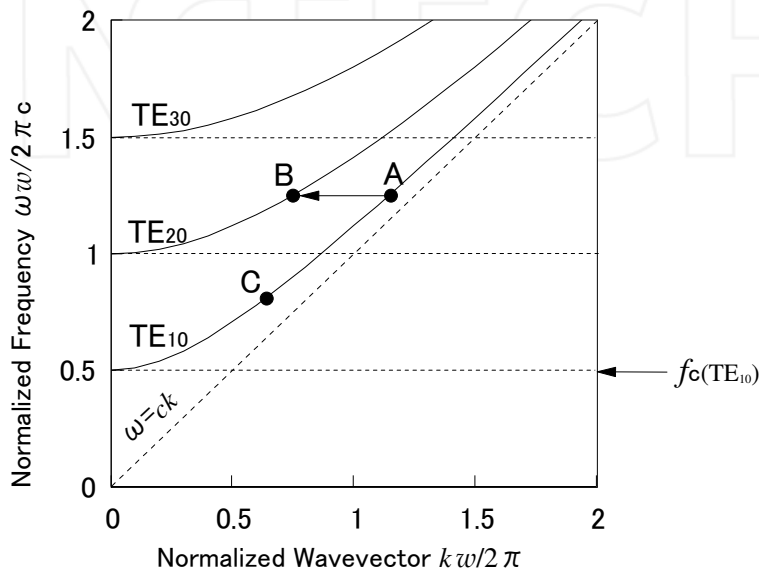


Fig. 1. The frequency eigenvalues of a conventional metallic waveguide in a given  $k$  wavevector.

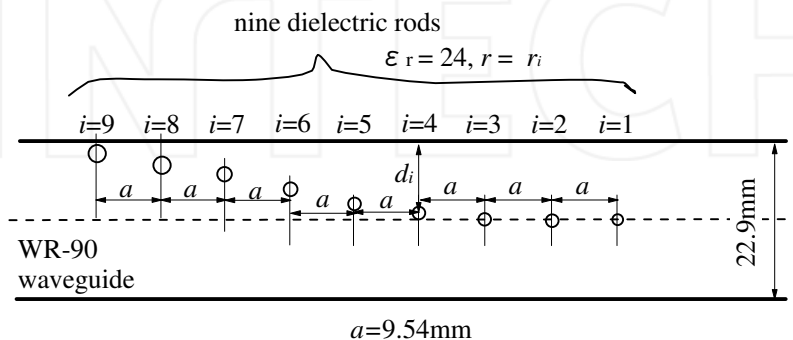


Fig. 2. The proposed structure of the  $TE_{10}$  to  $TE_{20}$  mode converter.

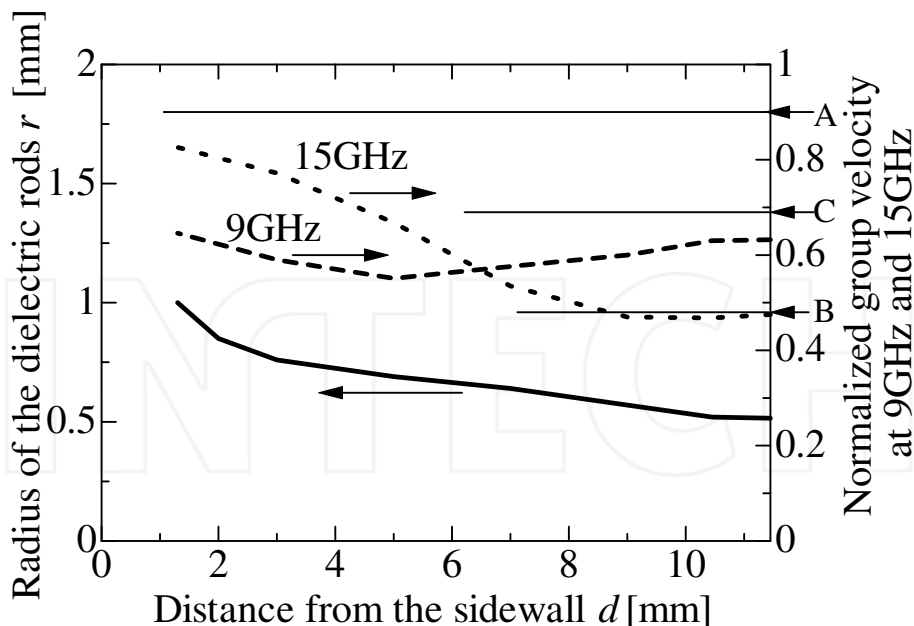


Fig. 3. The group velocity in a metallic waveguide with a periodic array of dielectric rods for various distances from the sidewall,  $d$ , and various radii of the rods,  $r$ , at 15 and 9 GHz. (Kokubo, 2010)

The group velocity is given by  $v_g = \frac{1}{(dk/d\omega)}$ . However, it is not simple to determine the

group velocity in the waveguide shown in Fig. 2. The propagation modes in a waveguide having in-line dielectric rods with period  $a$  are calculated using a supercell approach (Benisty, 1996) by application of appropriate periodic Bloch conditions at the boundary of the unit cell (Boroditsky et al.; Kokubo & Kawai, 2008). When the location of the dielectric rods is fixed at a distance  $d$  from the sidewall, the group velocity  $v_g$  at both of the first and the second bands is changed by varying the radius  $r$ . However, the group velocities are also changed at the same time and cannot be changed individually.

If the group velocity is normalized using light velocity in a vacuum,  $v_g/c$  is the same as the gradient of the characteristic curve. Therefore, when  $d$  and  $r$  are fixed to certain values,  $v_g/c$  is calculated for the periodic structure of the dielectric rods at a specific frequency. If group velocity (A) is gradually changed to (B) for  $1 < \omega w/2\pi c < 1.5$  when  $d$  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 a structure shown in Fig. 2.

The metallic waveguide is assumed to be a WR-90 (22.9×10.2 mm, cutoff frequency  $f_c \approx 6.55$ GHz) and period  $a$  is fixed at 9.54 mm. Fig. 3 shows a sample of calculated results of normalized velocity along the axis of the waveguide at 15 GHz and 9 GHz for dielectric rods (LaAlO<sub>3</sub>:  $\epsilon_r = 24$ , radius  $r$  [mm]) aligned at a distance from the sidewall  $d$  [mm] (Kokubo, 2010). It is desirable that the normalized velocity (A) (TE<sub>10</sub>:  $v_g/c = 0.900$ ) monotonically

decreases to (B) ( $TE_{20}$ :  $v_g/c = 0.487$ ) at 15 GHz and normalized velocity (C) ( $TE_{10}$ :  $v_g/c = 0.686$ ) is not changed at 9 GHz. However, at 15 GHz, such a condition is not found around  $d=10$  mm, because the placement of the dielectric rod at the center of the waveguide is the same as that where the electric field becomes a minimum. On the other hand, placement of the dielectric rod near the sidewall of the waveguide is the same as that where the electric field becomes a maximum. At the transition region, around  $d=10$  mm, the characteristics are complex. The design takes priority, in order to not vary the group velocity at 9 GHz. Since the group velocity must become slow with dielectric material at 9 GHz and becomes slowest at  $d=5$  mm, the design takes priority at 15 GHz for mode conversion, because both 15 GHz and 9 GHz conditions cannot be satisfied at the same time. The final design of the mode converter is shown in Fig. 2. Three dielectric rods are located at the center of the waveguide. Two of these have  $r = 0.515$  mm and the remainder have a half cross-section radius of 0.36 mm in order to decrease electromagnetic reflection. Nine dielectric rods are placed from the center of the waveguide to near the sidewall with increasing radius of the rods  $r$  and with constant  $a = 9.54$  mm. Table 1 shows the relation between the distance  $d$  and radius  $r$  (Kokubo, 2010). The S parameters between the input port (Port 1) and output. port (Port 2) are calculated using the HFSS software by Ansys Inc. and the results are shown as solid lines in Figs. 4(a) and (b). The electromagnetic waves pass through as the  $TE_{10}$  mode for 7-11.2 GHz and are converted to the  $TE_{20}$  mode for 14.1-16.1 GHz under a condition of over 95% efficiency. However, as the  $TE_{20}$  mode is not sufficiently small under -15 dB, optimization of the design is necessary for reduction of reflections. Though reflection as  $TE_{20}$  is not small at high frequency, if a coaxial-waveguide converter is used for the introduction of electromagnetic waves to a waveguide, odd mode may not have a strong influence on even symmetry structure.

Rod Number $i$	Distance $d_i$ from the Sidewall [mm]	Radius $r_i$ of the dielectric rod [mm]
1	11.45	0.36
2	11.45	0.515
3	11.45	0.515
4	10.45	0.52
5	9	0.57
6	7	0.64
7	5	0.69
8	3	0.76
9	1.3	1.0

Table 1. Location and radii of the dielectric rods

## 2.2 Simple fabrication method

For the fabrication of a mode converter, such as the Type A illustrated in Fig. 5(a), it is necessary to locate the dielectric rods in the waveguide without a gap at top and bottom. Such a structure may be difficult to fabricate. As a solution, holes with diameters 0.2 mm larger than the rods were fabricated at the top of the waveguide and the dielectric rods were inserted (Type B, Fig. 5(b)). The S parameters were calculated using the HFSS software and the results are shown as dotted lines in Figs. 4(a) and (b). The results for these different structural conditions (solid lines and dotted lines) are almost same.

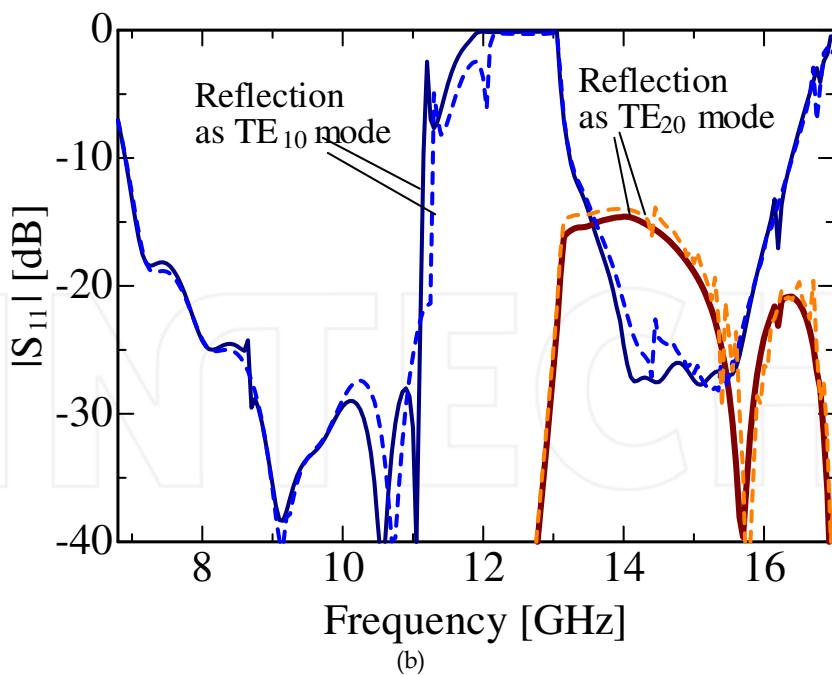
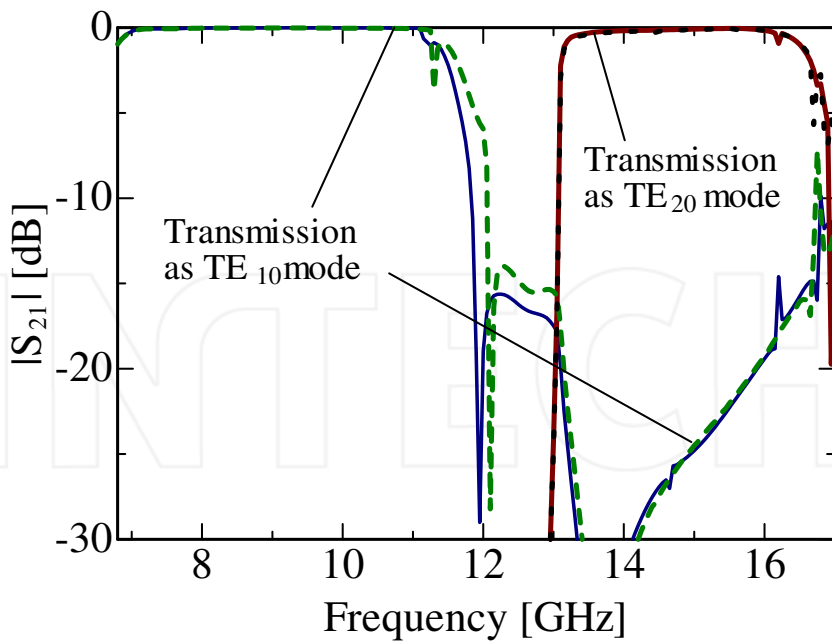


Fig. 4. S parameter for the mode converter; (a)  $|S_{21}|$  and (b)  $|S_{11}|$ . (Kokubo, 2010)

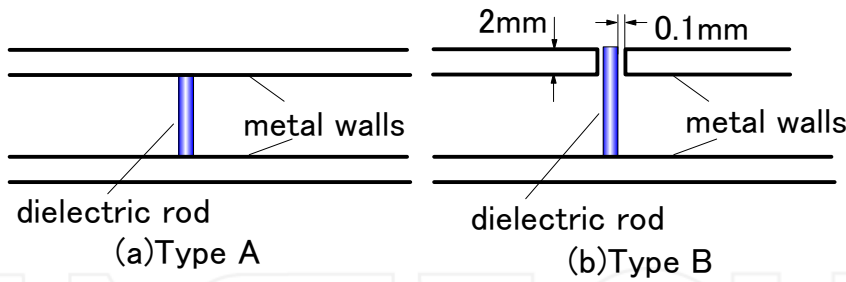


Fig. 5. (a) Dielectric rod located in a waveguide without gaps at top and bottom. (b) Dielectric rod inserted in a hole made at the top of the waveguide with a diameter 0.2 mm larger than the diameter of the rod. (Kokubo, 2010)

2.3 Reduction of reflection for TE<sub>20</sub> mode

As shown in Fig. 4(b), reflection as TE<sub>20</sub> mode is not small enough. This reason is dielectric rods are asymmetric arrangement for electromagnetic wave. Fig. 6 shows an improved structure of the TE<sub>10</sub> to TE<sub>20</sub> mode converter.

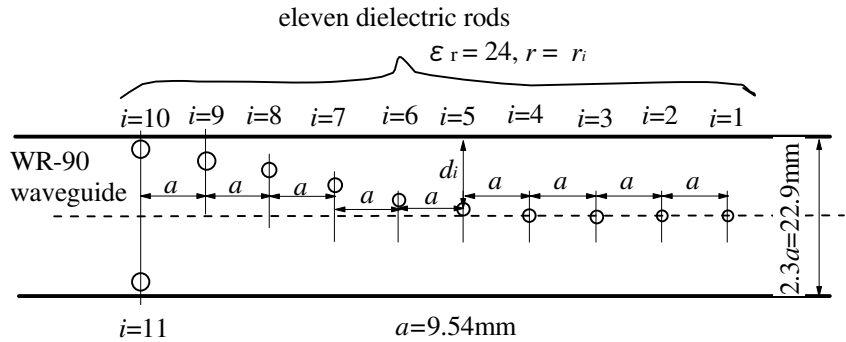
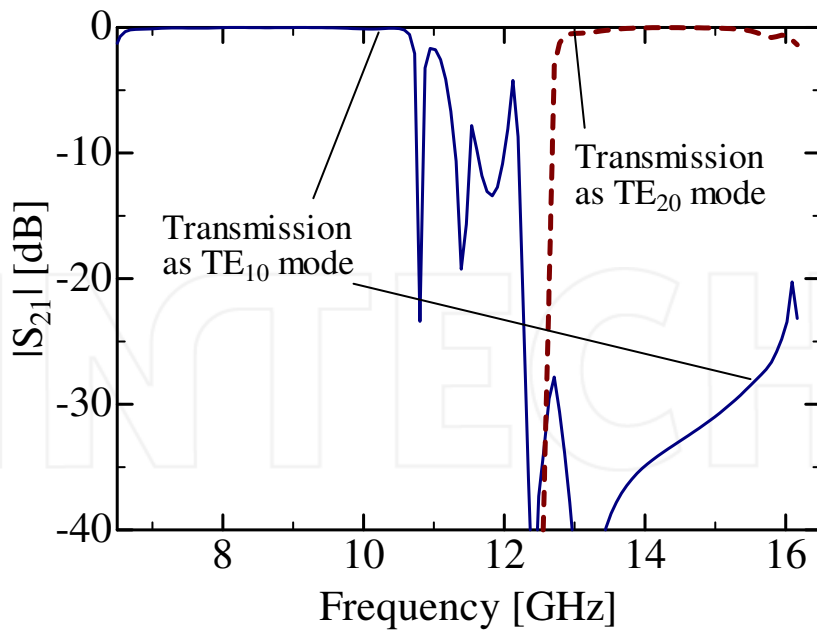


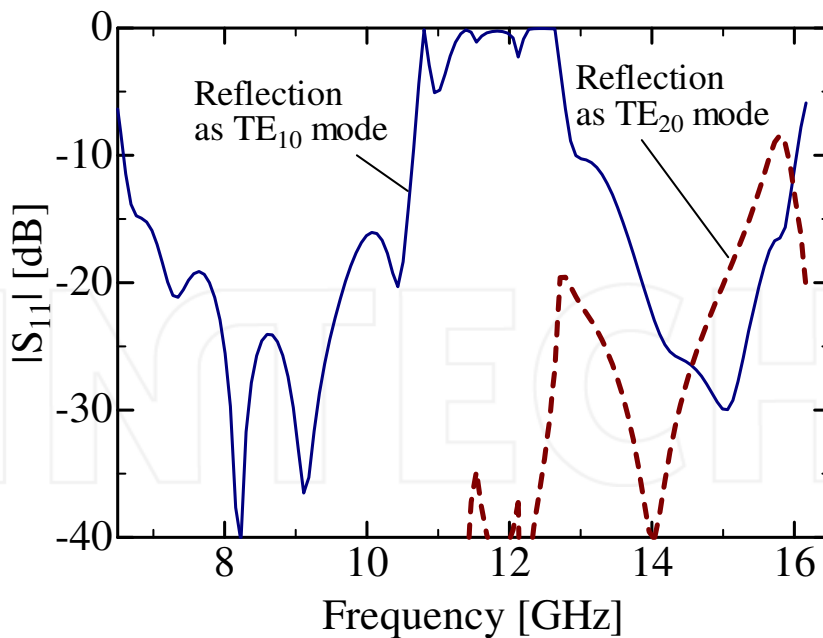
Fig. 6. An improved structure of the TE<sub>10</sub> to TE<sub>20</sub> mode converter.

Rod Number <i>i</i>	Distance <i>d<sub>i</sub></i> from the Sidewall [mm]	Radius <i>r<sub>i</sub></i> of the dielectric rod [mm]
1	11.45	0.38
2	11.45	0.55
3	11.45	0.55
4	11.45	0.55
5	10.45	0.515
6	9	0.57
7	7	0.64
8	5	0.69
9	3	0.76
10	1.25	0.92
11	21.65	0.96

Table 2. Location and radii of the dielectric rods



(a)



(b)

Fig. 7. S parameter for the mode converter; (a)  $|S_{21}|$  and (b)  $|S_{11}|$ .





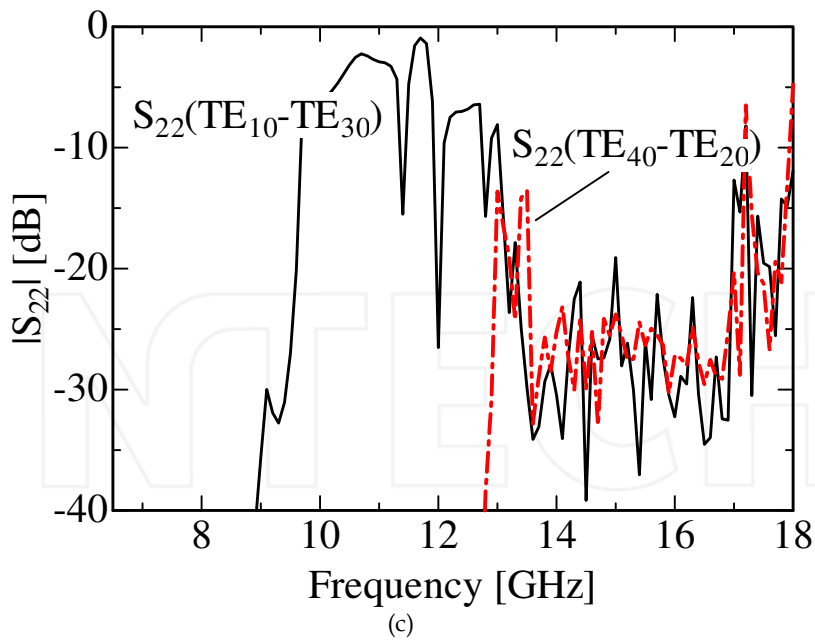
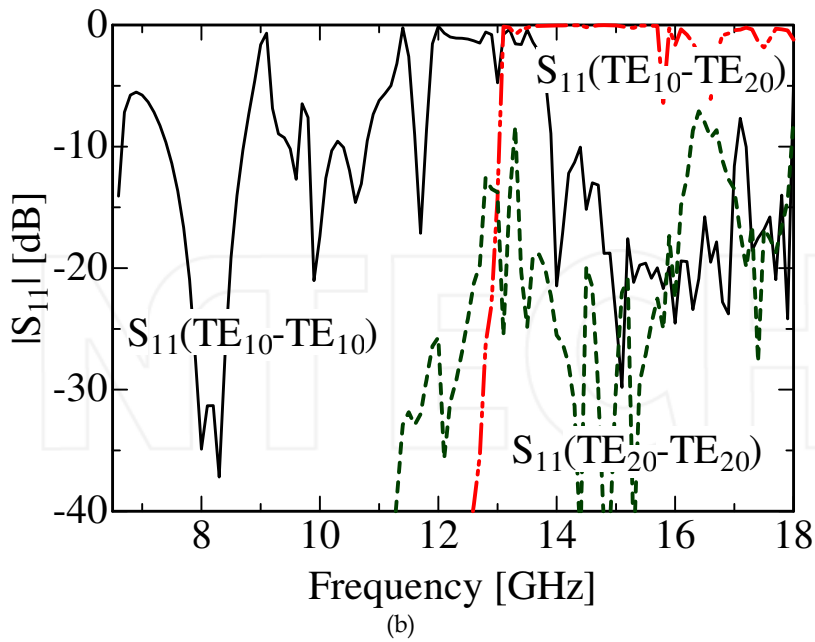


Fig. 10. S parameters for the TE<sub>10</sub>-to-TE<sub>40</sub> mode converter. (a)  $|S_{21}|$ , (b)  $|S_{11}|$ , and (c)  $|S_{22}|$ . (Kokubo, 2011a)

## 2.5 Design method of the TE<sub>30</sub>-to-TE<sub>10</sub> mode converter

A structure that contains two arrays of dielectric rods can convert the TE<sub>30</sub> mode into the TE<sub>10</sub> mode (Kokubo, 2009). The TE<sub>30</sub> mode electromagnetic waves in this type of waveguide are converted to the TE<sub>10</sub> mode for 7.1–8.9 GHz with over 95% efficiency. However, this structure cannot pass through electromagnetic waves around 2.5–3 GHz without high reflection even if the waveguide is straight. Therefore, a mode converter is proposed that passes the TE<sub>10</sub> mode at low frequencies and efficiently converts the TE<sub>30</sub> mode into the TE<sub>10</sub> mode at high frequencies.

A metallic waveguide that contains two in-line dielectric rods can propagate single modes in two frequency regions (Shibano et al., 2006). The propagation modes in a waveguide with two in-line dielectric rods with period  $a$  are calculated using a supercell approach (Benisty, 1996) by applying appropriate periodic Bloch conditions at the boundary of the unit cell (Boroditsky et al., 1998; Kokubo & Kawai, 2008).

The metallic waveguide width is assumed to be  $w_1 = 21.4$  mm, which is 3 times wider than the WR-28 waveguide ( $7.11 \times 3.56$  mm;  $f_c \approx 21.1$  GHz), and period  $a$  is fixed at 5 mm. Fig. 11 shows a sample of the calculated normalized velocity along the waveguide axis at 9 and 27 GHz for dielectric rods (LaAlO<sub>3</sub>:  $\epsilon_r = 24$ ; radius  $r$  [mm]) aligned at a distance  $w_2$  [mm] between two arrays. The waveguide must be designed so as not to vary the group velocity (C) (TE<sub>10</sub>:  $v_g/c = 0.627$ ) at 9 GHz. After calculating  $v_g$  for pairs of  $w_{2i}$  and  $r_i$ , if group velocity (A) (TE<sub>30</sub>:  $v_g/c = 0.627$ ) is gradually changed to (B) (TE<sub>10</sub>:  $v_g/c = 0.966$ ) at 27 GHz, then each pair of  $w_{2i}$  and  $r_i$  are combined (see Fig. 12).

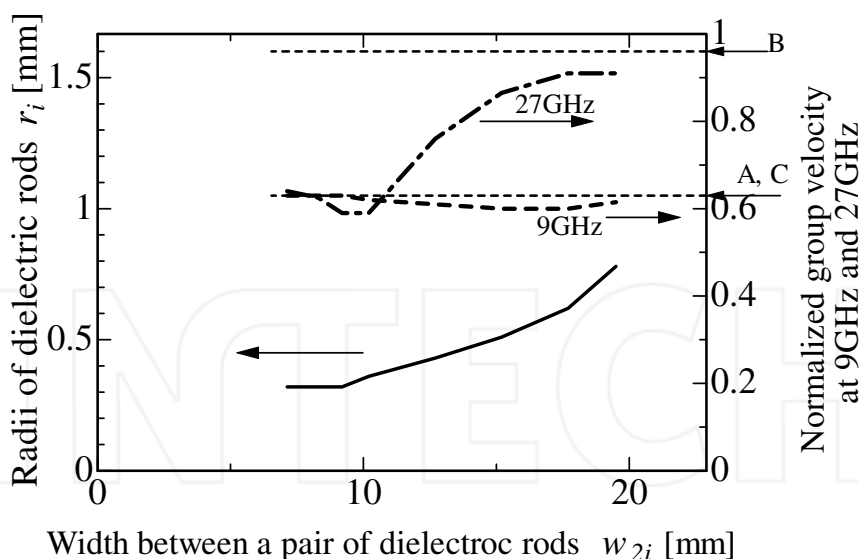


Fig. 11. Group velocity (dotted lines) in a metallic waveguide containing a periodic array of dielectric rods with various distances  $w_{2i}$  between the rods and corresponding radii  $r_i$  (solid line) of the rods, at 9 and 27 GHz. (Kokubo, 2011b)

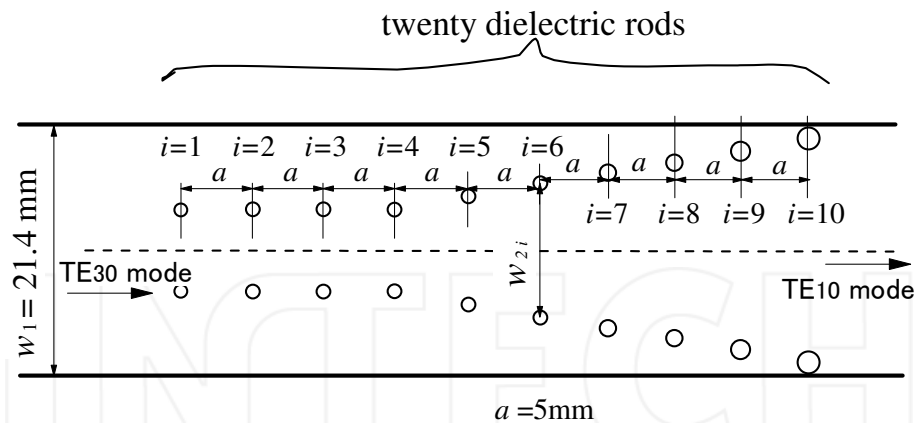
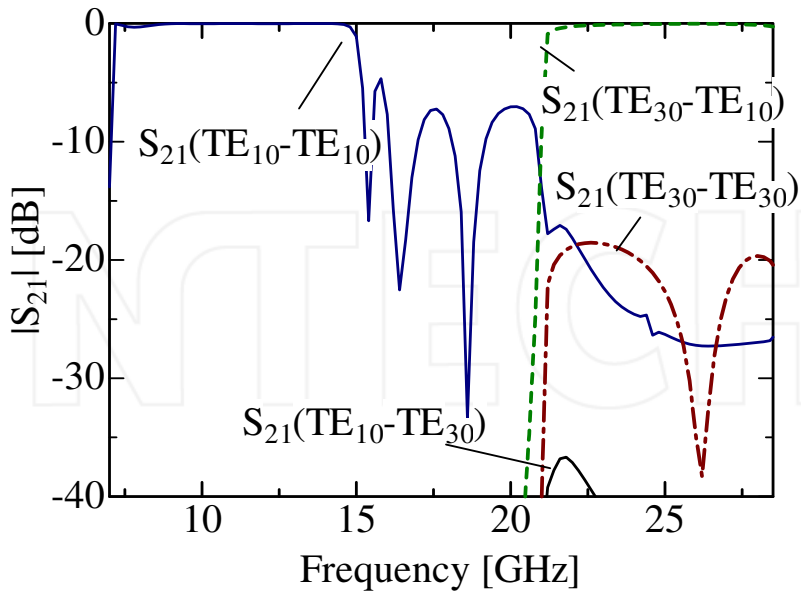


Fig. 12. Proposed structure of the TE<sub>30</sub>-to-TE<sub>10</sub> mode converter. (Kokubo, 2011b)

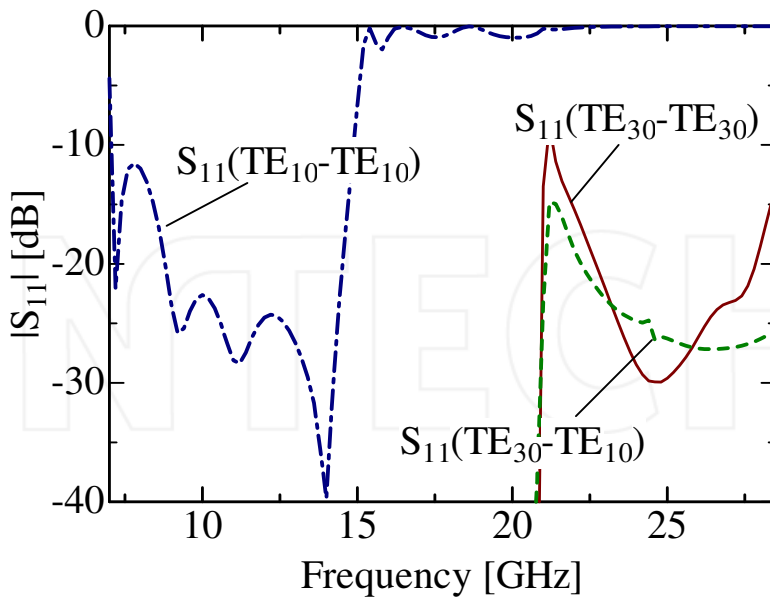
Rod Number $i$	Distance $w_{2i}$ between a pair of the rods [mm]	Radius $r_i$ of the dielectric rod [mm]
1	7.13	0.22
2	7.13	0.32
3	7.13	0.32
4	7.13	0.32
5	8.3	0.32
6	10.2	0.36
7	12.7	0.43
8	15.2	0.51
9	17.7	0.62
10	19.5	0.78

Table 3. Location and radius of the dielectric rods

The first pair of rods has  $r_1 = 0.22$  mm to reduce electromagnetic reflection at low frequencies. If the first pair of rods is absent, then reflections will be above  $-10$  dB at low frequencies. Twenty dielectric rods are placed from one third of the width of the waveguide to near the sidewall with increasing rod radius  $r_i$  and constant  $a (= 5$  mm). Table 3 shows the relation between the distance  $w_{2i}$  and radius  $r_i$ . The S parameters between the input port (port 1) and output port (port 2) are calculated using HFSS software by Ansys Inc., and the results are shown in Figs. 13(a-c). Electromagnetic waves propagate as the TE<sub>10</sub> mode for 8.2–14.8 GHz and the TE<sub>30</sub> mode is converted into the TE<sub>10</sub> mode for 22.2–28.4 GHz at an efficiency of over 95%.



(a)



(b)

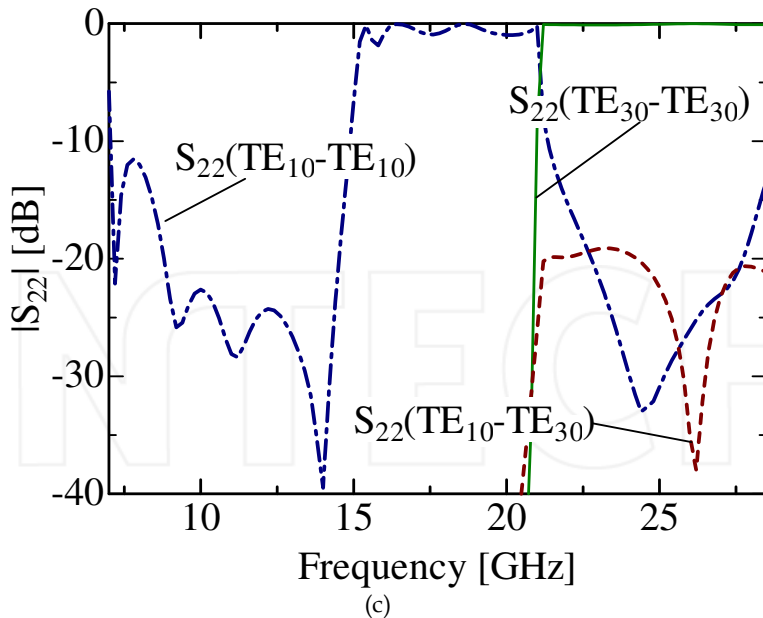


Fig. 13. S parameters for the mode converter; (a)  $|S_{21}|$ , (b)  $|S_{11}|$ , and (c)  $|S_{22}|$ . (Kokubo, 2011b)

### 3. Conclusion

We have previously reported that single-mode propagation is available for a metallic waveguide with dielectric rods arrayed at the center of a waveguide using the  $TE_{10}$  mode, and the  $TE_{20}$  mode. However, a  $TE_{20}$ -like mode, which is propagated in the second band, is an odd mode, and generation is not easy. In this investigation, a mode converter is proposed which passes through the  $TE_{10}$  mode for the low frequency range and converts  $TE_{10}$  to the  $TE_{20}$  mode for the high frequency range by small variation of the group velocity. It was shown that the electromagnetic waves pass through as the  $TE_{10}$  mode for 7-11.2 GHz and are converted to the  $TE_{20}$  mode for 14.1-16.1 GHz under a condition of over 95% efficiency.

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.

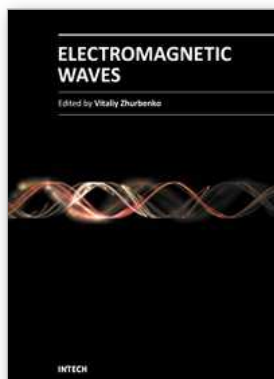
### 4. Acknowledgment

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This book is dedicated to various aspects of electromagnetic wave theory and its applications in science and technology. The covered topics include the fundamental physics of electromagnetic waves, theory of electromagnetic wave propagation and scattering, methods of computational analysis, material characterization, electromagnetic properties of plasma, analysis and applications of periodic structures and waveguide components, and finally, the biological effects and medical applications of electromagnetic fields.

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