

NTNU

TTT4205 MICROWAVE TECHNIQUES

Waveguide assignment

Magne H. Å. Haneberg

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1 Rectangular waveguide

1.1 Cut-off frequencies

The cut-off frequency of a hollow waveguide is given by

$$f_c^{(\text{mn})} = \frac{c}{2\pi\sqrt{\epsilon_r\mu_r}} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}. \quad (1)$$

For a *WR75* waveguide, modes TE_{10} and TE_{20} , the cut-off frequencies are $f_c^{(10)} = 7.8740$ GHz and $f_c^{(20)} = 15.748$ GHz.

The unimodal frequency band, ΔF , is given by

$$\Delta F = f_c^{(20)} - f_c^{(10)} = 7.8740 \text{ GHz}. \quad (2)$$

1.2 Normalized propagation constants

The propagation constant of a hollow waveguide is given by

$$k_z^{(\text{mn})} = \sqrt{k_0^2\epsilon_r\mu_r - \left(\frac{m\pi}{a}\right)^2 - \left(\frac{n\pi}{b}\right)^2} \quad (3)$$

where

$$k_0 = \frac{2\pi f}{c} = \frac{2\pi f}{3 \times 10^8 \text{ m/s}}. \quad (4)$$

For a *WR75* waveguide, modes TE_{10} and TE_{20} , from 5 to 25 GHz, the propagation constants are shown in figure 1.

1.3 Phase and group velocities

The phase and group velocities for the TE_{10} mode in the unimodal frequency band is given by equations 5 and 6 and plotted in figure 2.

$$V_{\text{ph}}^{(\text{mn})} = \frac{\frac{c}{\sqrt{\epsilon_r\mu_r}}}{\sqrt{1 - \left(\frac{f_c^{(\text{mn})}}{f}\right)^2}} \quad (5)$$

$$V_{\text{g}}^{(\text{mn})} = \frac{c}{\sqrt{\epsilon_r\mu_r}} \sqrt{1 - \left(\frac{f_c^{(\text{mn})}}{f}\right)^2} \quad (6)$$

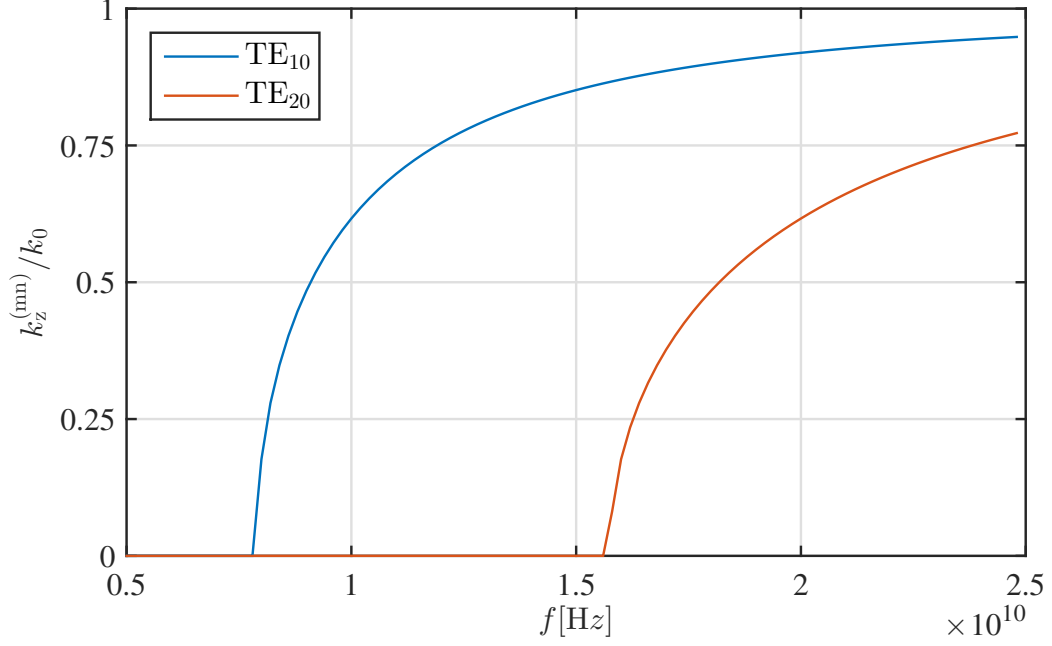


Figure 1: Normalized propagation constants in TE_{10} and TE_{20} modes.

1.4 Wave impedance

The wave impedance of a TE_{mn} mode is given by equation 7. This impedance is plotted for a TE_{10} wave in figure 3 for the unimodal frequency band.

$$W_{mn}^{\text{TE}} = \frac{\dot{E}_x^{(mn)}}{\dot{H}_y^{(mn)}} = \frac{\omega \mu_r \mu_0}{k_z^{(mn)}} = \sqrt{\frac{\mu_r \mu_0}{\epsilon_r \epsilon_0}} \frac{1}{\sqrt{1 - \left(\frac{f_c^{(mn)}}{f}\right)^2}} \quad (7)$$

1.5 Cut-off frequencies in an ideal dielectric

The cut-off frequencies for a waveguide is given by equation 1. If the waveguide is filled with air, this corresponds to $\epsilon_r = 1$. When filled with a perfect dielectric, ϵ_r changes value. However, it is still a real number.

The cut-off frequencies of a *WR75* waveguide filled with a perfect dielectric, $\epsilon_r = 2.44$, are shown in table 1.

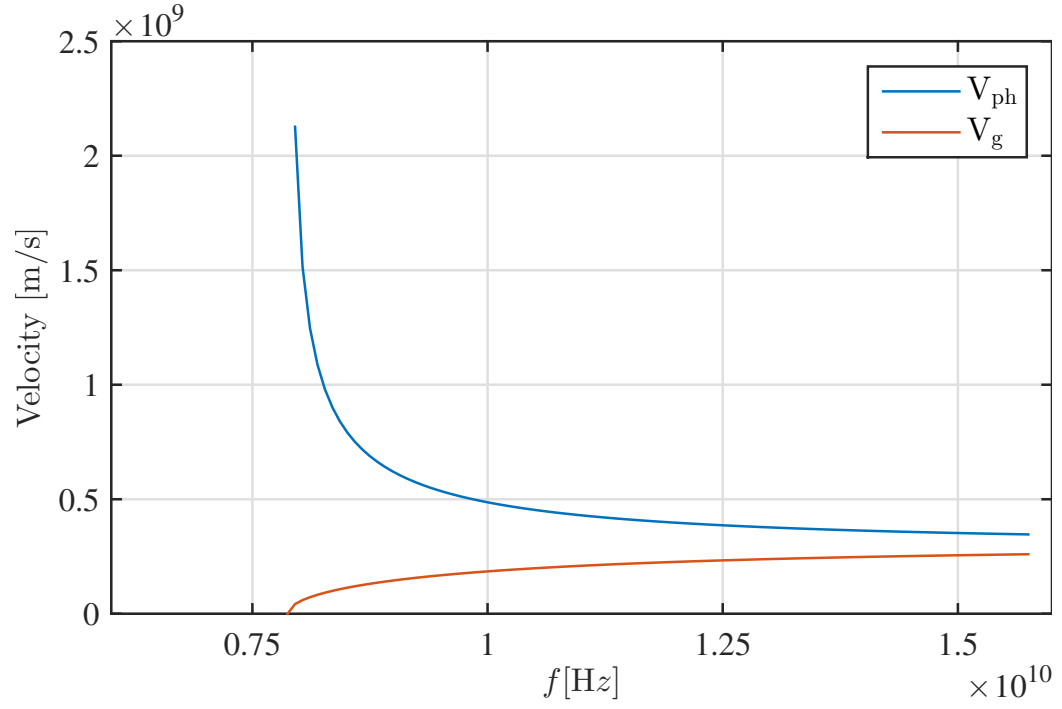


Figure 2: Phase and group velocities of TE_{10} wave in the unimodal frequency band

Table 1: Cut-off frequencies for waveguide filled with perfect dielectric

Mode	Cut-off frequency
TE_{10}	5.0408 GHz
TE_{20}	10.082 GHz

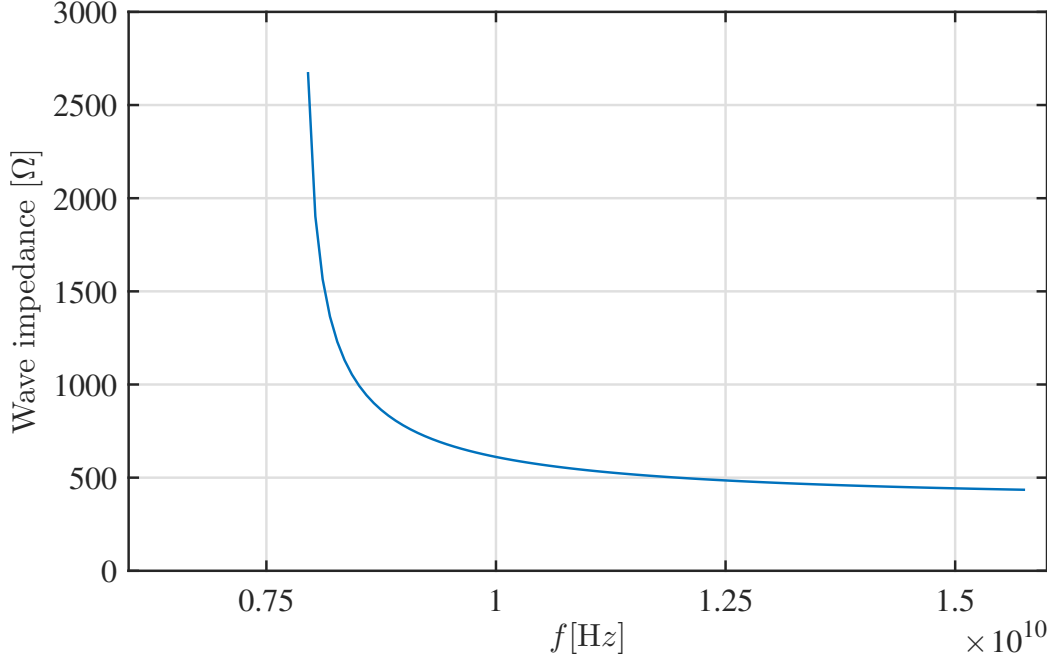


Figure 3: Wave impedance of TE₁₀ wave in the unimodal frequency band

1.6 Dielectric loss constant

The dielectric loss constant for a mode TE_{mn} is given by equation 8.

$$\alpha_d^{(mn)} = \frac{\Delta \bar{P}_{\text{loss/unit}}}{2\bar{P}} \approx \frac{\epsilon_r''}{\epsilon_r'} \frac{\pi}{\lambda} \left(\frac{\Lambda_{mn}}{\lambda} \right) \quad (8)$$

Λ_{mn} and λ are given by equations 9 and 10.

$$\Lambda_{mn} = \frac{2\pi}{k_z^{(mn)}} = \frac{\lambda}{\sqrt{1 - \left(\frac{f_c^{(mn)}}{f} \right)^2}} \quad (9)$$

$$\lambda = \frac{2\pi}{k_0 \sqrt{\epsilon_r \mu_r}}. \quad (10)$$

According to [1],

$$\epsilon_r'' = \epsilon_r' \tan \delta = \epsilon_r \epsilon_0 \tan \delta. \quad (11)$$

Given $\tan \delta = 0.002$, we have

$$\alpha_d^{(mn)} \approx \frac{k_0 \sqrt{\epsilon_r \mu_r}}{1000 \sqrt{1 - \left(\frac{f_c^{(mn)}}{f} \right)^2}}. \quad (12)$$

The dielectric loss constant is plotted for the unimodal frequency band in figure 4.

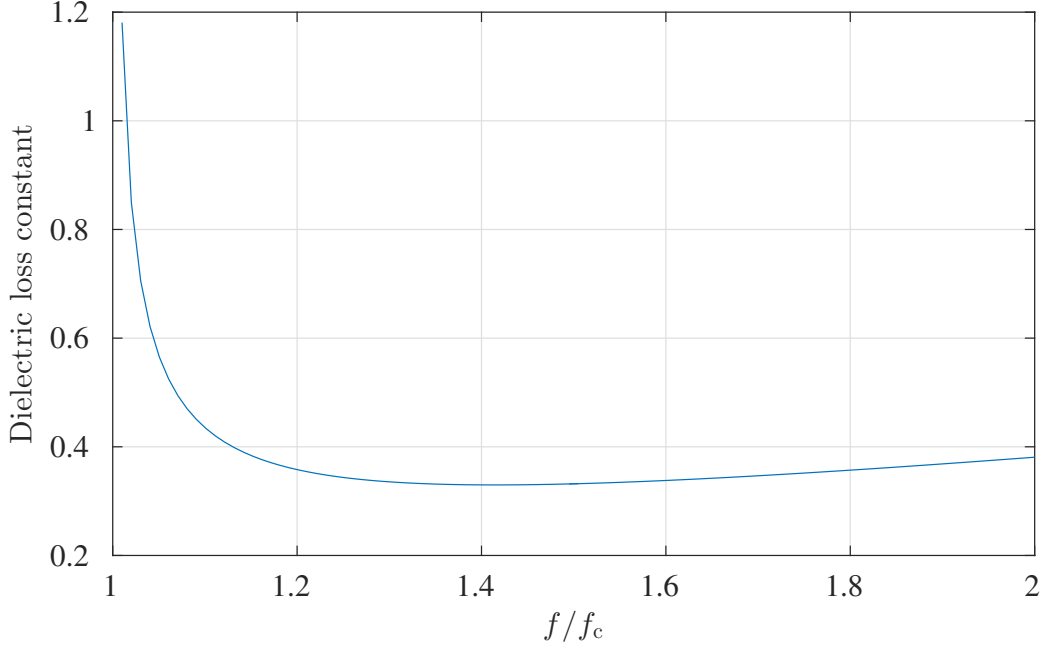


Figure 4: Dielectric loss constant, TE₁₀ wave.

1.7 Equivalent capacitance and inductance

The equivalent capacitance and equivalent inductance are given by equations 13 and 14, respectively.

$$C_{\text{equ}} \approx \frac{2k_z^{(10)}b}{\pi^2 f W_{10}^{\text{TE}}} \ln \left[\csc \left(\frac{\pi s}{2a} \right) \right] \quad (13)$$

$$L_{\text{equ}} \approx \frac{a\mu_r\mu_0}{2\pi \cot^2 \left(\frac{\pi s}{2a} \left[1 + \csc^2 \left(\frac{\pi s}{2a} \right) \right] \right)} \quad (14)$$

The equivalent capacitance is plotted in figure 5.

The equivalent inductance does not vary with frequency. For the specified waveguide, $L_{\text{equ}} \approx 2.1633 \times 10^{-8}$ H/m.

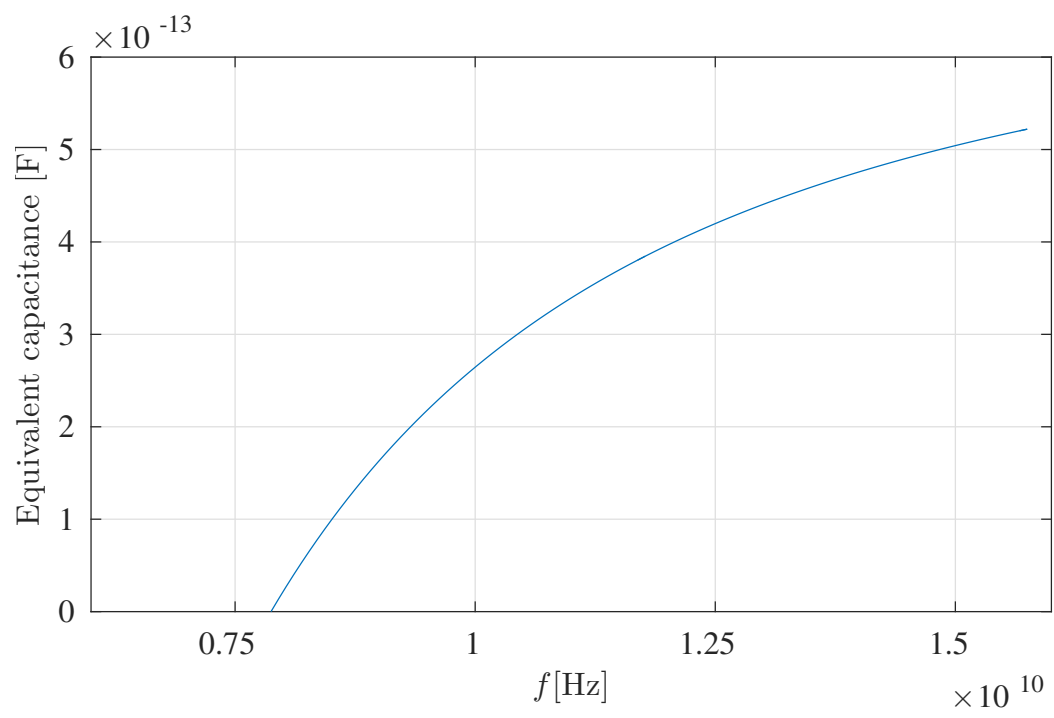


Figure 5: Equivalent capacitance over the unimodal frequency band.

2 Microstrip line

2.1 Effective permittivity

The effective permittivity relies on the geometry of the microstrip line. It is given by equation 15.

$$\epsilon_{\text{eff}}(f = 0) = \left(\frac{\beta}{k_0} \right)^2 = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2\sqrt{1 + \frac{10h}{W}}} \quad (15)$$

Given the geometry $h = 1 \text{ mm}$ and $W = (0.1 \dots 4) \text{ mm}$, with $\epsilon_r = 3.32$, the effective permittivity becomes as plotted in figure 6.

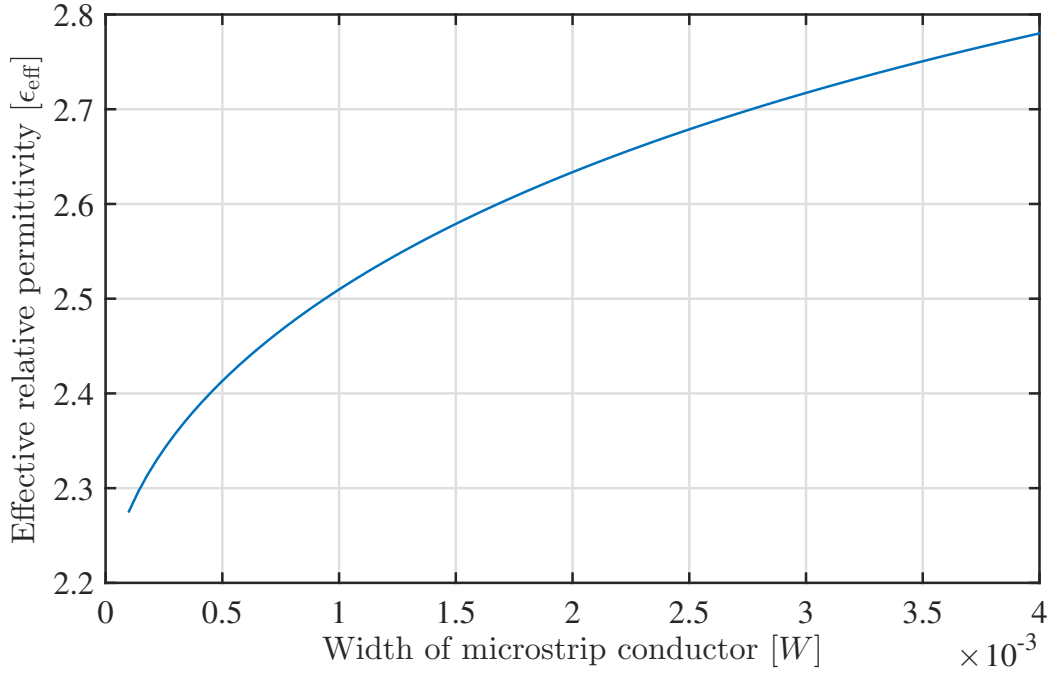


Figure 6: Effective relative permittivity of microstrip line.

2.2 Characteristic impedance

The characteristic impedance of a microstrip line is given by equation 16.

$$Z_c = \begin{cases} \frac{60}{\epsilon_{\text{eff}}(f=0)} \ln \left(\frac{8h}{W} + \frac{0.25W}{h} \right) & \frac{W}{h} < 1 \\ \frac{120\pi}{\sqrt{\epsilon_{\text{eff}}(f=0)} \left[\frac{W}{h} + 1.393 + 0.667 \ln \left(\frac{W}{h} + 1.444 \right) \right]} & \frac{W}{h} \geq 1 \end{cases} \quad (16)$$

Given the geometry $h = 1$ mm and $W = (0.1 \dots 4)$ mm, with $\epsilon_r = 3.32$, the characteristic impedance becomes as plotted in figure 7.

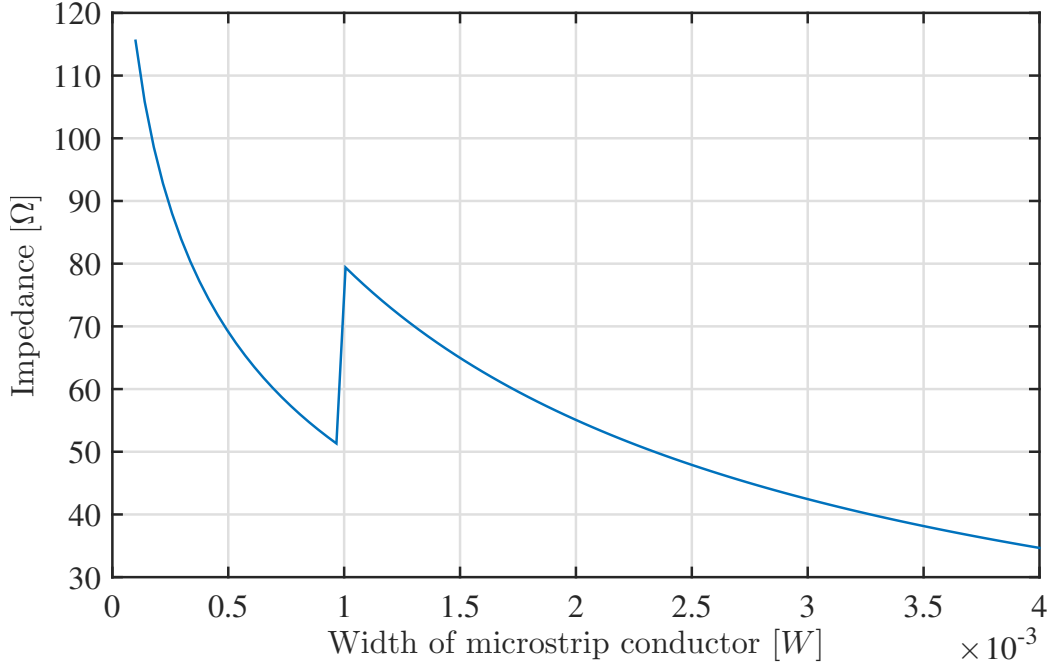


Figure 7: Characteristic impedance of microstrip line.

2.3 S-matrix coefficients

The S-matrix coefficients, transmission and reflection, are given by equations 17 and 18. They are plotted in figure 8.

$$T = \frac{2\sqrt{Z_c^{(2)} Z_c^{(1)}}}{Z_c^{(2)} + Z_c^{(1)}} \quad (17)$$

$$R = \frac{Z_c^{(2)} - Z_c^{(1)}}{Z_c^{(2)} + Z_c^{(1)}} \quad (18)$$

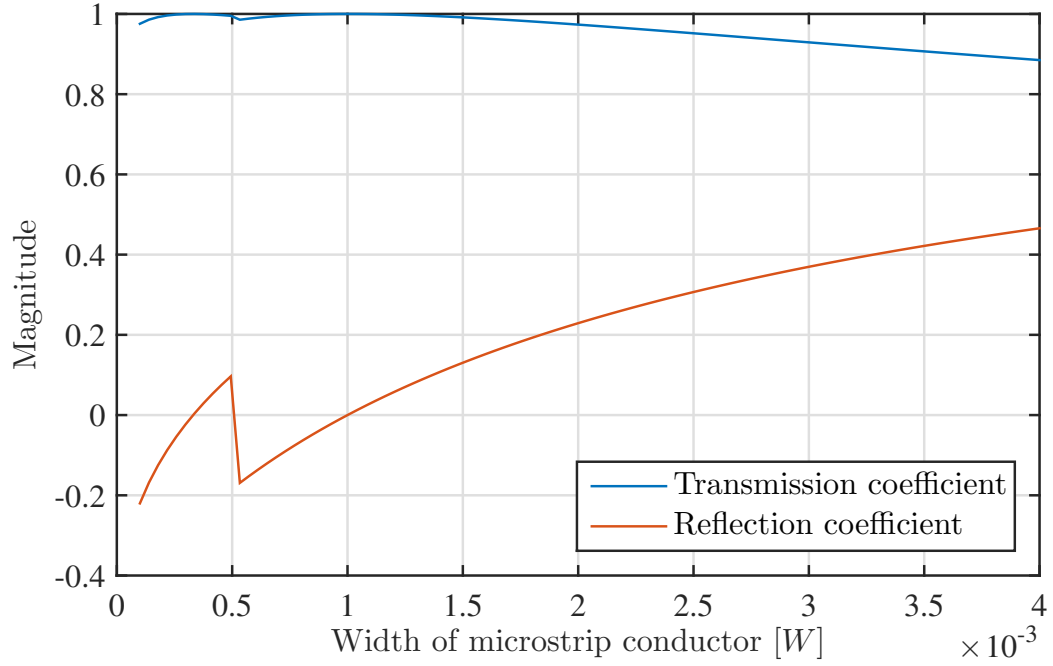


Figure 8: S-matrix coefficients of microstrip line.

3 Microstrip Branch-Line Directional Coupler

The *Keysight ADS tools* can be used to calculate the geometry of a microstrip branch-line directional coupler. Inserting the following values into ADS, the results in table ?? are obtained.

- $F_0 = 1.6 \text{ GHz}$
- $h = 1 \text{ mm}$
- $\epsilon_r = 3.32$
- $Z_0 = 50 \Omega$

Table 2: Branch-line coupler geometry

Parameter	Size
TE_{10}	5.0408 GHz
TE_{20}	10.082 GHz

References

- [1] larebok mikrobolge