マイクロ波測定
−負荷インピーダンス測定−

1st 2013/09/25

Lst 2024/02/05

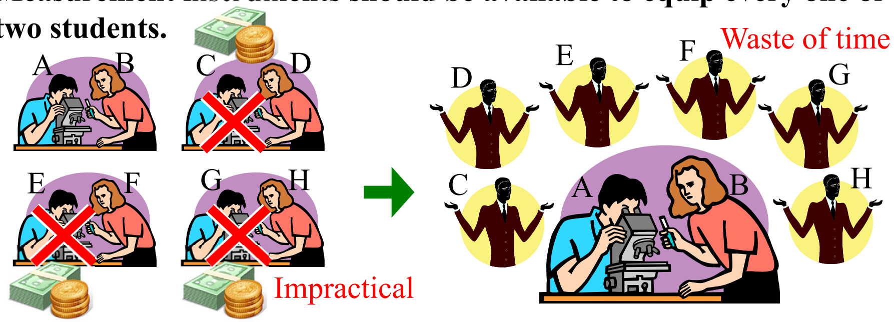
Introduction

In microwave engineering, standing wave pattern measurement system, circuit network analyzer, and combination of spectrum analyzer and ...re used

Specialized measurement system is expensive

Motivation / Aims

Measurement instruments should be available to equip every one or two students.

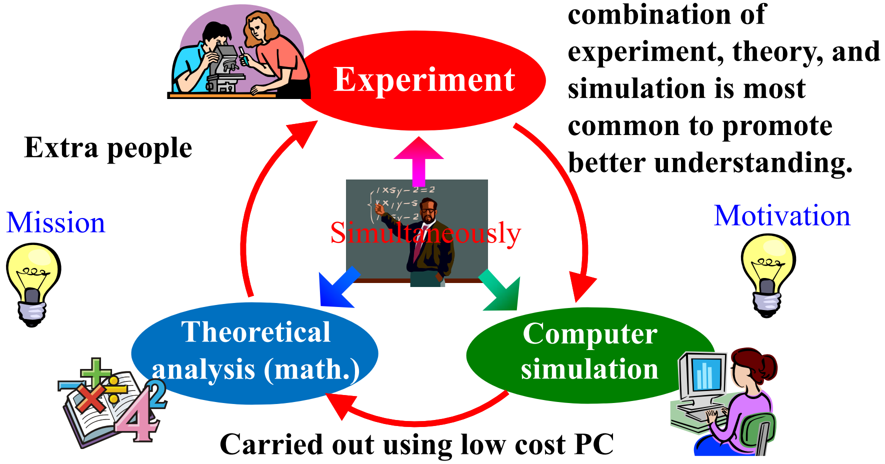


Simultaneously sharing a single precision measurement instrument among a whole group is also unworkable.

How do we manage a grope within the constraints of time and money ?

Methodology

The use of triple combination of experiment, theory, and simulation is most common to promote better understanding.



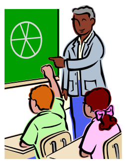
The load on the teaching assistant will increase with increasing number of sub-themes.

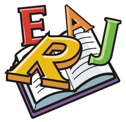
Constrains / Plans

Constraints

- Available measurement instrument is only one
- A group member consists of six to eight people
- Total allocated time is 6 hours

Program flow

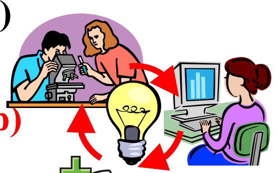




1. **Introduction (0.5 h, whole)**
2. **Example reading (1 h, whole)**
3. **Measurement (1 h, subgroup)**

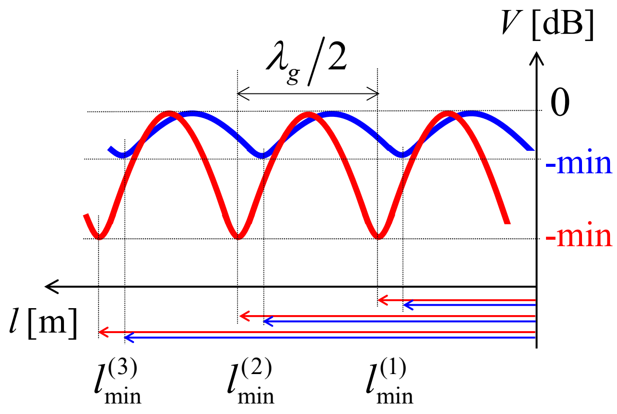
3+. Simulation(1 h, subgroup)

3++. Calculation(1 h, subgroup)



4. **Data analysis (1 h, whole)**
5. **Oral exam (0.5 h, 5 min. each)**

Measurement parameters



(1) Wavelength

λ_g [m] f [Hz]

(2) Minimum amplitude

$-\min$ [dB]

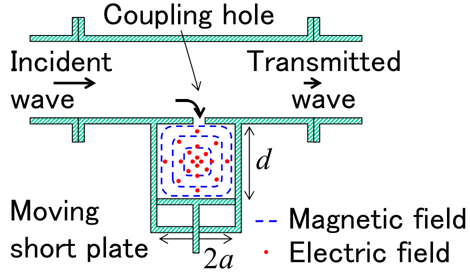
(3) Length at minimum point

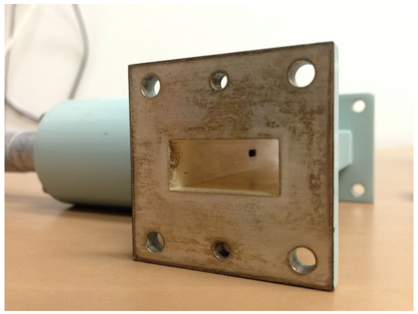
$l_{\min}$ [m]

Three measurement values are required for derivation of the unknown load impedance.

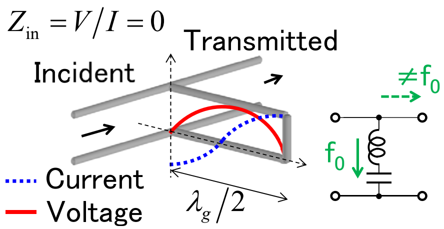
Frequency measurement

Cavity frequency meter



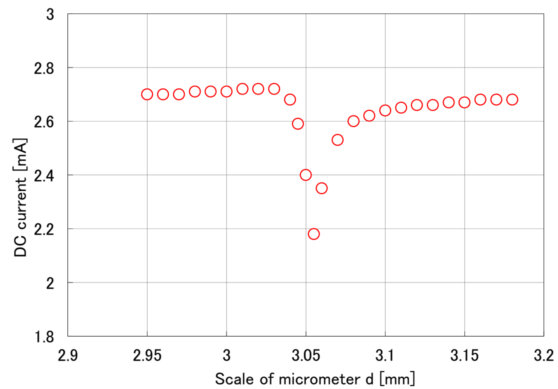


Transmission line model



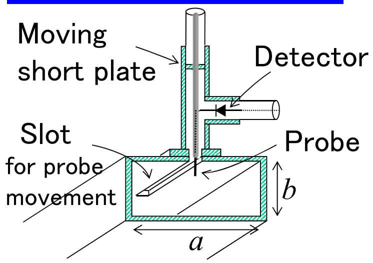
When an incident wave is coupled with a hole in half-wave resonance, the input impedance measured at the incident port becomes zero. When this occurs, the incident wave is completely reflected back to the source.

Measured resonant current

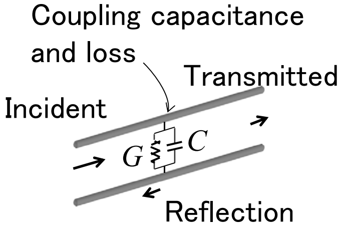


Electric field probe

Standing wave meter



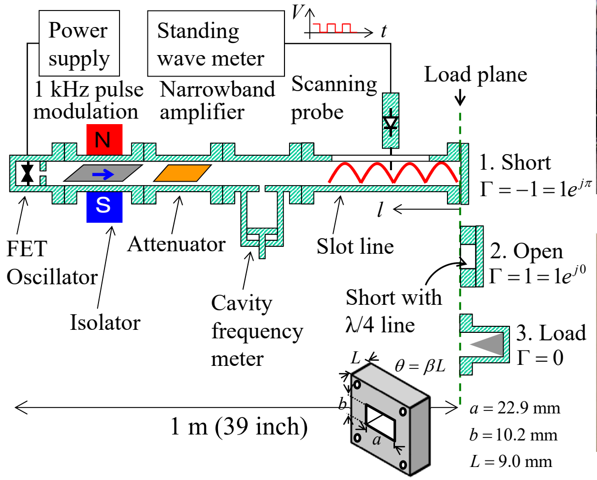
Transmission line model

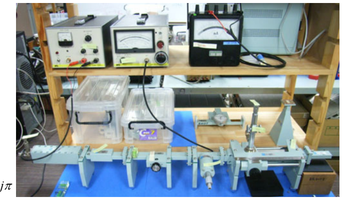


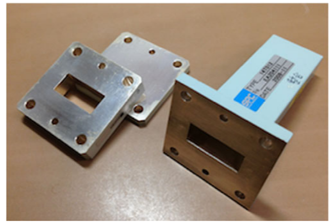
The waveguide center is slotted for electric probe movement. However, the inserted probe will generate a shunt capacitance and conductance in the transmission line.

Experimental setup (detailed)

- Standing wave pattern measurement system-



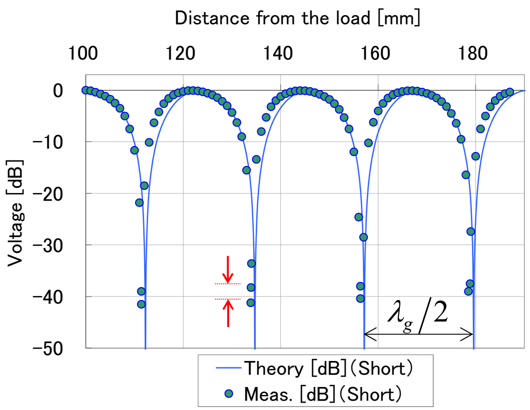


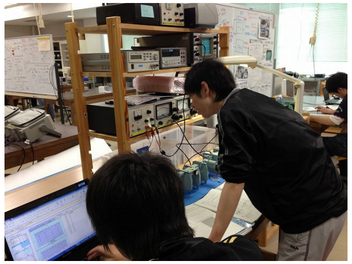


User's manual of microwave experimental instrument. 14T150A, SPC Electronics Corp.

Measured results

- Short condition @9.357 GHz -





This result appears to show a good agreement with the theory.

Theoretical pattern

$|\Gamma| =$

$\theta =$

$\lambda_g =$

$\beta =$

x [mm]	$y = f(\|\Gamma\|, \theta, \beta, x)$	$20\log_{10}(y/y_{\max})$
100	$=\sqrt{1+\|\Gamma\|^2+2\|\Gamma\|\cos(\theta-2\beta x)}$	$=20\log_{10}(y/y_{\max})$
101	数式コピー	数式コピー
102		
・		
・		
・	※数式をコピーする際に x のみ相対参照とし、$\|\Gamma\|$, θ, β は絶対参照にする。	
190		

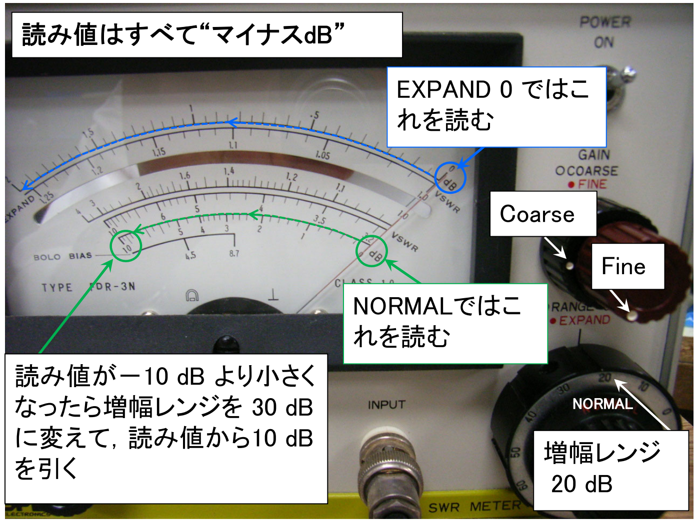
$$\lambda_g = \frac{\lambda_0}{\sqrt{1-(\lambda_0/2a)^2}}, \qquad \beta = \frac{2\pi}{\lambda_g}$$

ショート，オープン，整合の各ケースのΓとθの理論値は？

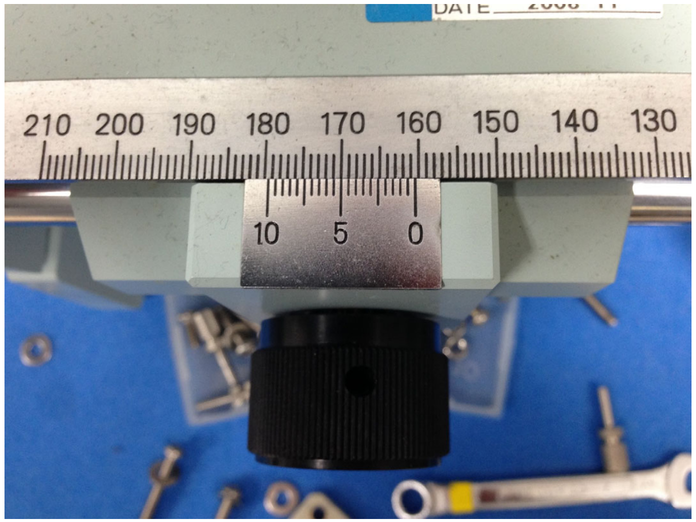
Theoretical parameters

	Ex. 2.4より抽出	Short (theory)	Open (theroy)	Load (theory)	Ref.
Z_L [Ω]	49.3+j19.7	1.000E-10	1.000E+10	50.0000	
Γ	0.0126+j0.1996	-1.0000	1.0000	0.0000	Eq.(6)
|Γ|	0.2000	1.0000	1.0000	0.0000	=ABS(Γ)
VSWR	1.5000	5.000E+11	2.000E+08	1.0000	Eq.(3)
freq [Hz]	N/A	9.300E+09	9.300E+09	9.300E+09	
λ_0 [m]	N/A	0.0323	0.0323	0.0323	=c/freq
λ_g [m]	0.0400	0.0454	0.0454	0.0454	Eq.(9)
β [rad/m]	157.0796	138.2692	138.2692	138.2692	Eq.(8)
θ [°]	86.4000	180.0000	0.0000	0.0000	
l_{min} [m]	0.0148	0.0000	-0.0114	-0.0114	Eq.(5)
l_{min}/λ_g	0.3700	0.0000	-0.2500	-0.2500	

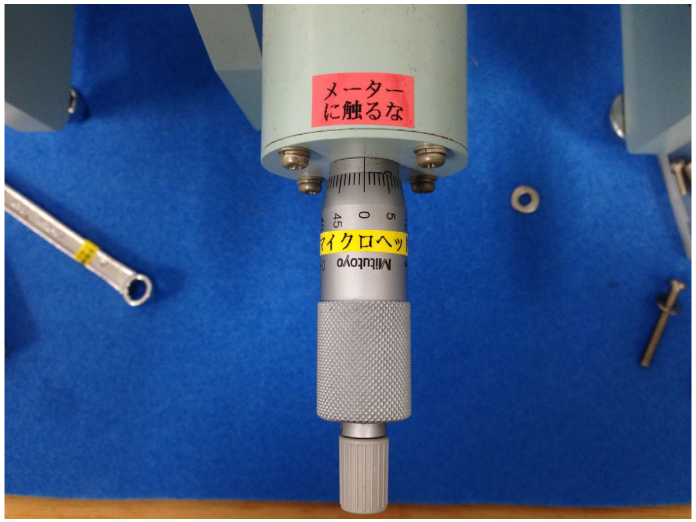
定在波増幅器の読み方



定在波測定器の読み方



空洞周波数計の読み方



Simulation conditions

- OS : Linux (Fedora, CentOS, …)
- Software : Gnuplot
- Wave mode : Plane wave in free space
- Frequency : 10 GHz
- Simulation parameter : Γ in complex

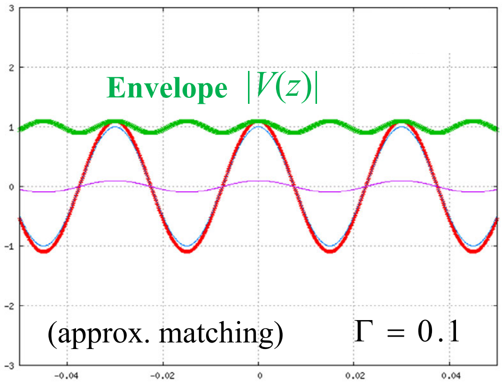
$$V(z) = \underbrace{e^{j(\omega t - \beta z)}}_{\text{Incident wave}} + \underbrace{\Gamma e^{j(\omega t + \beta z)}}_{\text{Reflected wave}} \quad (1)$$

$$|V(l)| = \underbrace{\left|1 + |\Gamma| e^{j(\theta - 2\beta l)}\right|}_{\text{Envelope of the standing wave}} = \sqrt{1 + |\Gamma|^2 + 2|\Gamma|\cos(\theta - 2\beta l)} \quad (2)$$

In this step, students are encouraged to create script files.

Simulated results

$$V(z) = \overbrace{\underbrace{e^{j(\omega t - \beta z)}}_{\text{Incident wave}} + \underbrace{\Gamma e^{j(\omega t + \beta z)}}_{\text{Reflected wave}}}^{\text{Standing wave}} \quad (1)$$



Students are instructed to write down the simulated results. Then, they come to understand the image of standing wave.

Theoretical analysis

- Standing wave ratio

$$\text{SWR} = \frac{V_{\max}}{V_{\min}} = 10^{\frac{|\text{Min[dB]}|}{20}} \quad (1)$$

- Absolute value of reflection coefficient

$$|\Gamma| = \frac{\text{SWR} - 1}{\text{SWR} + 1} \quad (2)$$

- Phase angle of reflection coefficient

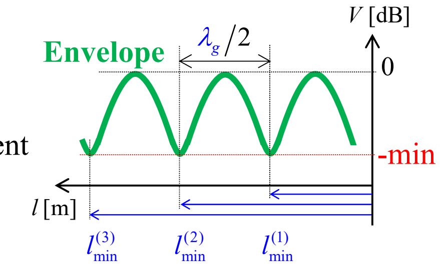
$$\theta = \pi + 2\beta\left(l_{\min} + \frac{n}{2}\lambda_g\right) \qquad n = 0, 1, 2, \cdots \quad (3)$$

- Complex reflection coefficient

$$\Gamma = |\Gamma| e^{j\theta} \quad (4)$$

- Normalized load impedance

$$z_L = \frac{Z_L}{Z_0} = \frac{1+\Gamma}{1-\Gamma} \quad (5)$$



Because of time constraints, it is considered inefficient to ask students to hand calculate the normalized impedance using a scientific electronic calculator.

Theoretical analysis

- Excel spread sheet for impedance calculation -

	A	B	C
1	v 6.3e Jan.2012 Impedance calculation sheet		
2			Example 2.4
3	Light velocity [m/s]	c	3.00E+08
4	Pai	π	3.141593
5	Frequency [Hz]	f	9.958E+09
6	Waveguide width [m]	a	0.02290
7	Freespace wavelength [m]	λ0	0.03013
8	Guided wavelength [m] (calc.)	λg	0.04000
10	Guided wavelength [m] (meas.)	λg	0.04000
11	Phase constant [rad/m]	β	157.08
12	Voltage standing wave ratio	SWR	1.50
13	Voltage minimum length [m]	ℓmin	0.01480

Measured values

- Frequency
- Wavelength
- VSWR
- $l_{\min}$

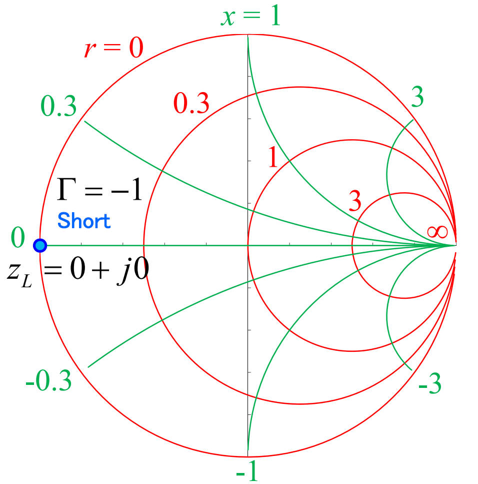
C20 = (1-POWER(C18,2)-POWER(C19,2))/(POWER(1-C18,2) +POWER(C19,2))

20	Real part of normalized impedance [Ω]	Re[zL]	0.95
21	Imaginary part of normalized impedance [Ω]	Im[zL]	0.39

Impedance is calculated automatically.

Smith Chart

- Plotting on Smith chart by Excel -

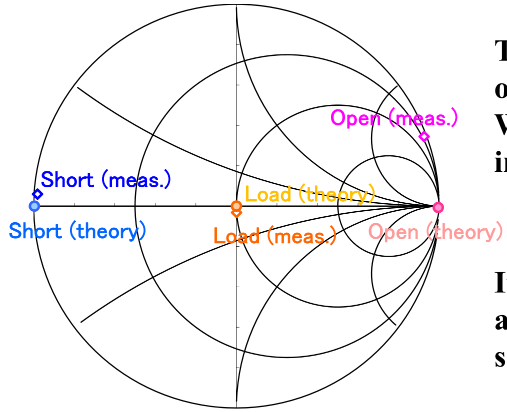


The Smith chart is a polar plot of the reflection coefficient that can be used to derive the load impedance graphically.

Y. Konishi, Y. Sugio & H. Shiomi, (2003). *RF / Microwave circuit CAD and Programing*. Tokyo: K-Laboratory.

Analytical results

- Plotting on Smith chart by Excel macro-



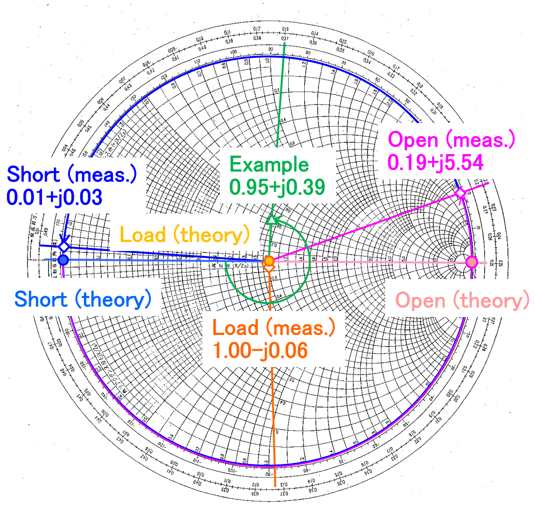
The Smith chart is a polar plot of the reflection coefficient. We can understand the load impedance schematically.

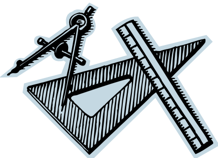
It seems to be a good agreement is obtained in the short and load conditions.

Y. Konishi, Y. Sugio & H. Shiomi, (2003). *RF / Microwave circuit CAD and Programing*. Tokyo: K-Laboratory.

Final results

- Handwriting version of Smith chart -





The only parameters that must be entered are SWR and l_{min} /λ_g.

負荷インピーダンスの測定

Example 2.4 Impedance Measurement with a Slotted Line

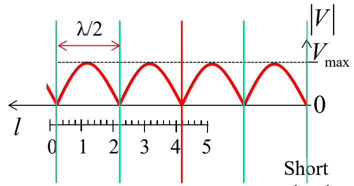
The following two-step procedure has been carried out with a 50 Ω coaxial slotted line to determine an unknown impedance:

1. A short circuit is placed at the load plane, resulting in a standing wave on the line with infinite SWR, and sharply defined voltage minima, as shown in Figure 2.14a. On the arbitrarily positioned scale on the slotted line, voltage minima are recorded at $z = 0.2$ cm, 2.2 cm, 4.2 cm.
2. The short circuit is removed, and replaced with the unknown load. The standing wave ratio is measured as SWR = 1.5, and voltage minima, which are not as sharply defined as those in step 1, are recorded at $z = 0.72$ cm, 2.72 cm, 4.72 cm, as shown in Figure 2.14b.

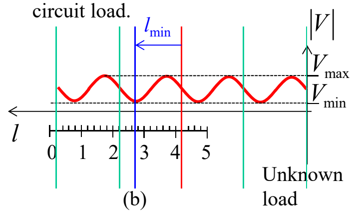
Find the load impedance.

Solution

Knowing that voltage minima repeat every λ/2, we have from the data of step 1 above that λ = 4.0 cm. In addition, because the reflection coefficient and input impedance also repeat every λ/2, we can consider the load terminals to be effectively located at any of the voltage minima locations listed in step 1. Thus, if we say the load is at 4.2 cm, then the data from step 2 shows that the next voltage minimum away from the load occurs at 2.72 cm, giving l_{min} = 4.2-2.72 = 1.48 cm = 0.37λ.



(a) Standing wave for short-circuit load.



(b) Standing wave for unknown load.

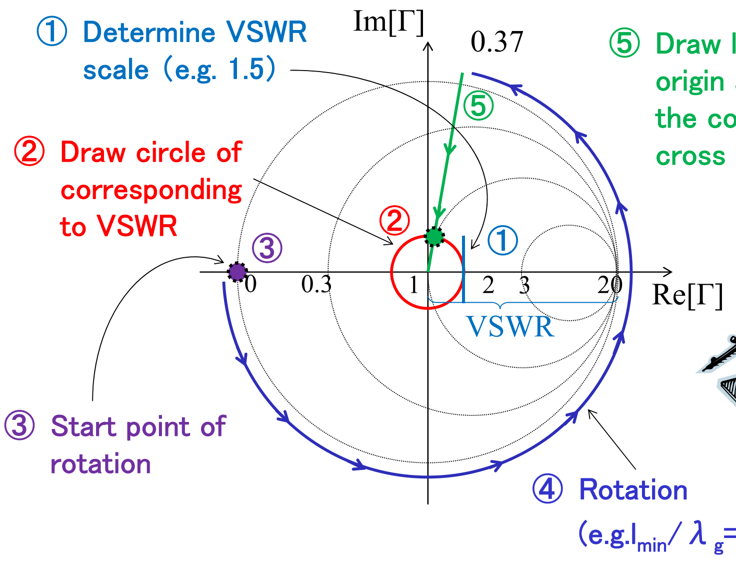
$|\Gamma| = 0.2, \theta = 86.4°,$

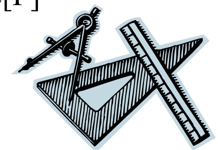
$\Gamma = 0.0126 + j0.1996,$

$Z_L = 47.3 + j19.7\,\Omega$

D. M. Pozar, Microwave Engineering, 3rd ed., pp.71−72 より引用

スミスチャートプロット手順





スミスチャートプロット手順

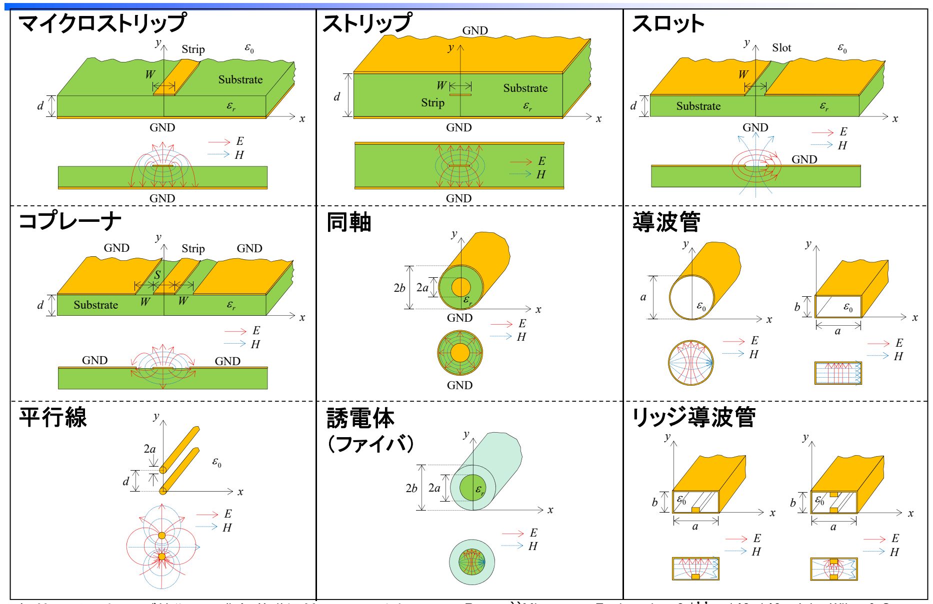
Example 2.4 Impedance Measurement with a Slotted Line

For the Smith chart version of the solution, we begin by drawing the SWR circle for SWR=1.5, as shown in Figure 2.15; the unknown normalized load impedance must lie on this circle. The reference that we have is that the load is 0.37λ away from the first voltage minimum. On the Smith chart, the position of a voltage minimum corresponds to the minimum impedance point (minimum voltage, maximum current), which is the horizontal axis (zero reactance) to the left of the origin. Thus, we begin at the voltage minimum point and move 0.37λ toward the load (counterclockwise), to the normalized load impedance point, $z_L = 0.95 + j0.4$, as shown in Figure 2.15. The actual load impedance is then $Z_L = 47.5 + j20\Omega$, in close agreement with the above result using the equations. Note that, in principle, voltage maxima locations could be used as well as voltage minima positions, but voltage minima are more sharply defined than voltage maxima, and so usually result in greater accuracy.

① VSWRに相当する円の半径を決める。VSWRの値は実軸に目盛られた抵抗分R/Z0の数値に等しい（例題では1.5）。VSWR > 30のときはほぼ全反射と考えてよい。当然，VSWR = ∞ のときは完全な全反射である。
② 原点を中心としてVSWRに相当する円を描く。
③ 左端の最小点を回転の始点とする。
④ 始点から波長換算した距離lmin/λg（例題では0.37）だけ負荷方向へ回転させる。
⑤ 回転させた位置から原点に向かって直線を引き，交点座標を読む。（例題ではzL=0.95+ j 0.4が得られればOK）

D. M. Pozar, Microwave Engineering, 3rd ed., pp.72-72 より引用

伝送線路の例（その1）



森, ``マイクロウェーブ技術入門講座 基礎編,'' p.14, CQ出版, 2003.　Pozar, ``Microwave Engineering, 3rd,'' p.143-146, John Wiley & Sons

Oral exams

It is important to confirm the final level of understanding of each student. To this end, the following oral questions are given to each student:

- What is a standing wave?
- What is load impedance? What does short, open or load mean in reference to the electric circuit?
- What can it do by Smith chart? Which is the reactance circle? Which is the resistance circle? Where is the short, open, load on the Smith chart?
- What is a waveguide? Describe the difference with other transmission lines using an example.