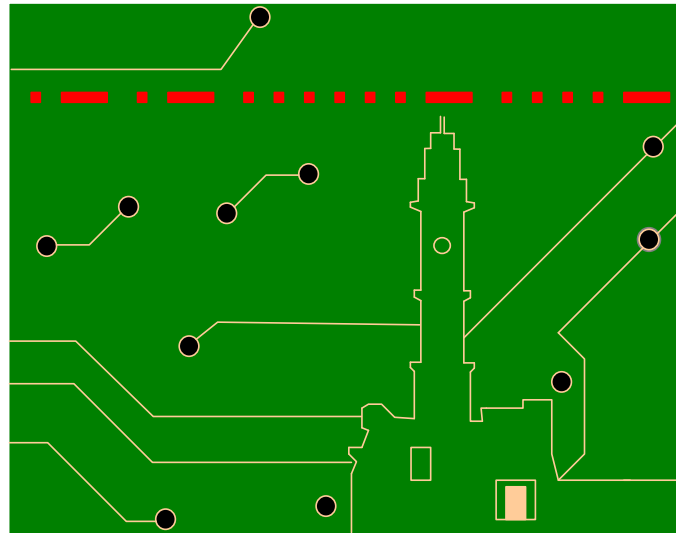


ΤΗΛ412 Ανάλυση & Σχεδίαση (Σύνθεση) Τηλεπικοινωνιακών Διατάξεων

Διαλέξεις 11-12

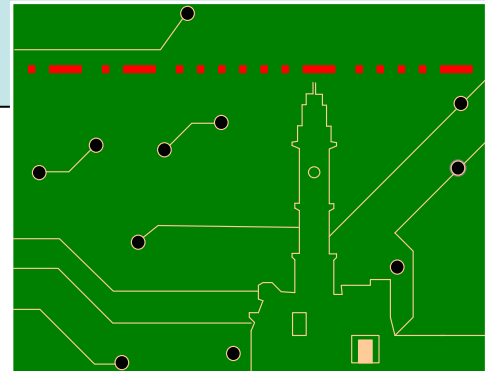


Άγγελος Μπλέτσας

ΗΜΜΥ Πολυτεχνείου Κρήτης, Χειμερινό Εξάμηνο 2016-2017

Διαλέξεις 11, 12 – Μικροκυματική Μηχανική (Microwave Engineering)

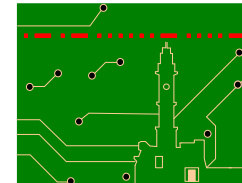
- Γραμμές Μεταφοράς.
- Παράμετροι Σκέδασης (Scattering Parameters).
- Διάγραμμα Smith.
- Προσαρμογή Εμπέδησης (Impedance Matching)
με Διάγραμμα Smith.



Βιβλιογραφία Διαλέξεων

Kai Chang, “RF and Microwave Wireless Systems”, Wiley Series in Microwave and Optical Engineering, John Wiley & Sons, 2000.

Βασική ερώτηση μαθήματος:



Τί είναι ο Δικτυακός Αναλυτής (Network Analyzer)?



In-Line, N-Jack Connectors

- Broadband Frequency (0.7 - 2.7 GHz)
- Low Insertion Loss (0.2 dB avg) ?
- High Isolation (30 dB avg)
- Excellent VSWR (1.10 : 1 avg)
- Tri-Alloy Plated Connectors for Low PIM

RADIO NEWS FOR FEBRUARY, 1934 403

LEARN RADIO FROM REAL RADIO ENGINEERS

HERE THEY ARE:

- Dr. C. F. Manly, Director, Radio Institute
- Frank E. Adams, Chief Engineer, Radio Institute
- Walter C. Smith, Chief Engineer, Radio Institute
- Charles L. Smith, Chief Engineer, Radio Institute
- Walter C. Smith, Chief Engineer, Radio Institute
- Walter C. Smith, Chief Engineer, Radio Institute
- Walter C. Smith, Chief Engineer, Radio Institute
- Walter C. Smith, Chief Engineer, Radio Institute
- Walter C. Smith, Chief Engineer, Radio Institute
- Walter C. Smith, Chief Engineer, Radio Institute

LET THESE ENGINEERS RIGHT FROM THE HEART OF THE BIG RADIO INDUSTRY Train You at Home for GOOD PAY RADIO WORK MANY R. T. I. TRAINED MEN MAKE \$35 TO \$75 A WEEK

If you're dissatisfied with small pay—work that's getting you nowhere—lay-off and uncertain income—here's an opportunity that's too good to miss. At the cost of only the time it takes you to mail the coupon, you can get my big FREE book, "RADIO'S FUTURE AND YOURS." This book tells you how you can learn at home to make more money almost at once in Radio—whether you want to make Radio your life's work, or use it to pick up an extra \$5 to \$20 a week in your spare time.

"RADIO IS GROWING BY LEAPS AND BOUNDS!"

my Radio Craft Magazine. It has forged a lead even in depression years. Where only a few hundred men were employed a short time ago, thousands are employed today. Where a few years ago a hundred jobs paid \$35 to \$75 a week—there are thousands of such jobs today. And more new jobs being created all the time—full time jobs and spare time jobs. Get my book and see how easy it is to learn at home for this good-pay work.

R. T. I. TRAINING IS "SHOP TRAINING" FOR THE HOME

It comes to you right from the Radio Industry—right out of the factories where Radio sets and other vacuum-tube devices are made. It was planned and prepared for you by big radio engineers in these factories, most of whom are the Chief Engineers of these great Radio plants. And NOW these same engineers are actually supervising R-T-I Training. Which means that trained the R-T-I way you'll be trained—as just as the Radio Industry itself, would train you if it was doing the job.

4 BIG WORKING OUTFITS INCLUDED

These are probably the biggest and most expensive Working Outfits ever included with a home-training course. You are then to build up testing equipment—to experiment with—to do actual Radio work. It's Shop Training for the home.

WE'RE OK

RADIO and TELEVISION INSTITUTE HOME TRAINING

say these 30 Leading Radio Manufacturers and they are talking to YOU

AMERICAN TELEVISION
ARCTURUS TUBES
BALKEIT • BRUNSWICK
CAPEHART
CLOUGH-BREngle CO.
CROSLEY • CLARION
DeFOREST • ECHOPHONE
FADA • GREBE • HOWARD
HAMMERLUND • HICKOK
INTERNATIONAL
RESISTANCE CO.
KENNEDY • KOLSTER • LYRIC
MAJESTIC • PHILCO
RADIO PRODUCTS CO.
SANGAMO ELECTRIC
SENTINEL • SHEDDEN
SILVER-MARSHALL CO.
STEWART-WARNER
STROMBERG-CARLSON
UNIVERSAL MICROPHONE
ZENITH

YOUR MONEY BACK IF YOU ARE NOT SATISFIED

That's my way of doing business. And I'll give you that agreement in writing—an agreement to refund every penny of your tuition if, on completion of my Training, you are not entirely satisfied.

INVESTIGATE!

Learn why R-T-I Training is different. Find out why R-T-I Trained men get "Quick Results" and "Big Results." Send today for my big book "Radio's Future and Yours." The book is free.

RAY D. SMITH, President
Radio & Television Institute, Chicago

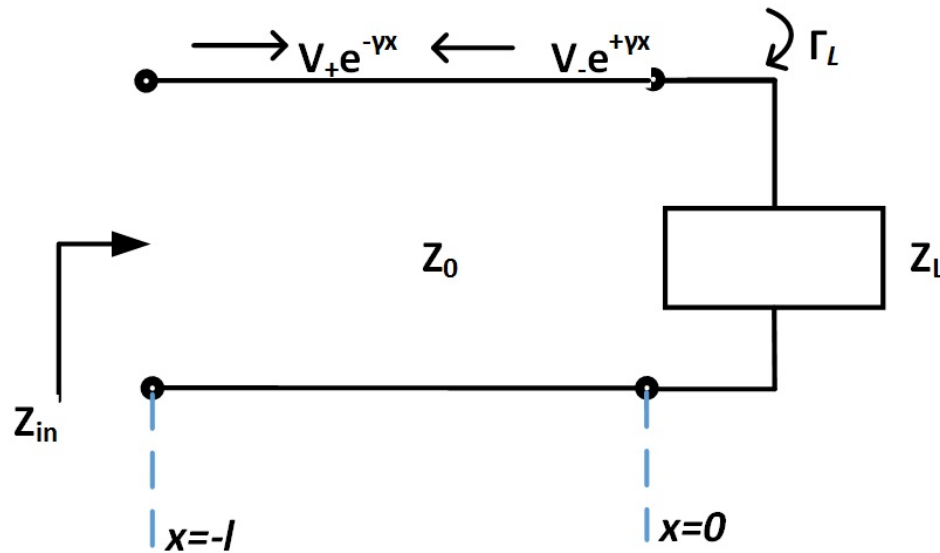
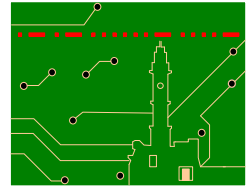
MAIL COUPON FOR MY FREE BOOK

On your copy of "Radio's Future and Yours" I have already marked the name of the nearest representative. In sending my Coupon, it tells what R. T. I. institute you desire and enables me to FREE. THE FREE BOOK!

Ray D. Smith, President
Radio and Television Institute, 201 E. 11th St., Des Moines, Ia.
I am interested in your "Radio's Future and Yours." I am interested in your home training and the opportunity you give to the great field of Radio for the R. T. I. Trained men.

Name _____
Address _____
City _____ State _____

Γραμμή Μεταφοράς (Transmission Line): Επισκόπηση



$$\frac{d^2 V(x)}{dx^2} - \gamma^2 V(x) = 0$$

$$V(x) = V_+ e^{-\gamma x} + V_- e^{+\gamma x}$$

$$I(x) = I_+ e^{-\gamma x} + I_- e^{+\gamma x}$$

➤ γραμμή με απώλειες:

$$\gamma = [(R + j\omega L)(G + j\omega C)]^{1/2} = \alpha + j\beta$$

$$Z_0 = \frac{V_+}{I_+} = \frac{V_-}{I_-} = \frac{R + j\omega L}{\gamma} = \left(\frac{R + j\omega L}{G + j\omega C} \right)^{1/2}$$

➤ γραμμή με απώλειες: παρασιτικό R κατά μήκος του αγωγού, παρασιτικό G μεταξύ των αγωγών.

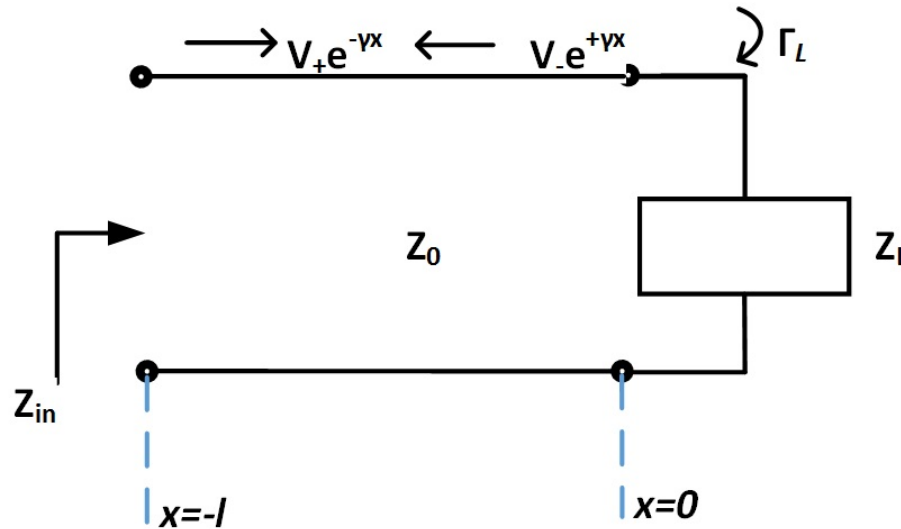
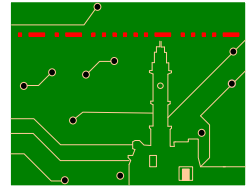
➤ γραμμή χωρίς απώλειες:

$$\gamma = j\beta = j\omega\sqrt{LC}$$

$$Z_0 = \sqrt{\frac{L}{C}}$$

$$u_p = \frac{\omega}{\beta} = f\lambda_g = \frac{1}{\sqrt{LC}}$$

Γραμμή Μεταφοράς: Γενικές Εξισώσεις

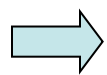


$$\Gamma(x) = \frac{\text{reflected } V(x)}{\text{incident } V(x)} = \frac{V_- e^{\gamma x}}{V_+ e^{-\gamma x}} = \frac{V_-}{V_+} e^{2\gamma x}$$

$$\Gamma_L = \frac{V_-}{V_+} = \Gamma(0) = \frac{I_-}{I_+}$$

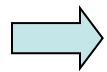
➤ Εμπέδηση (impedance) εισόδου ως συνάρτηση του μήκους της γραμμής:

$$Z(x) = \frac{V(x)}{I(x)} = Z_0 \frac{e^{-\gamma x} + \Gamma_L e^{\gamma x}}{e^{-\gamma x} - \Gamma_L e^{\gamma x}} = Z_0 \frac{1 + \Gamma(x)}{1 - \Gamma(x)}$$

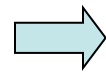


$$Z_L = Z_0 \frac{1 + \Gamma_L}{1 - \Gamma_L}$$

$$\Gamma_L = |\Gamma_L| e^{j\phi} = \frac{Z_L - Z_0}{Z_L + Z_0}$$



$$Z_{in} = Z(-l) = Z_0 \frac{e^{\gamma l} + \Gamma_L e^{-\gamma l}}{e^{\gamma l} - \Gamma_L e^{-\gamma l}}$$

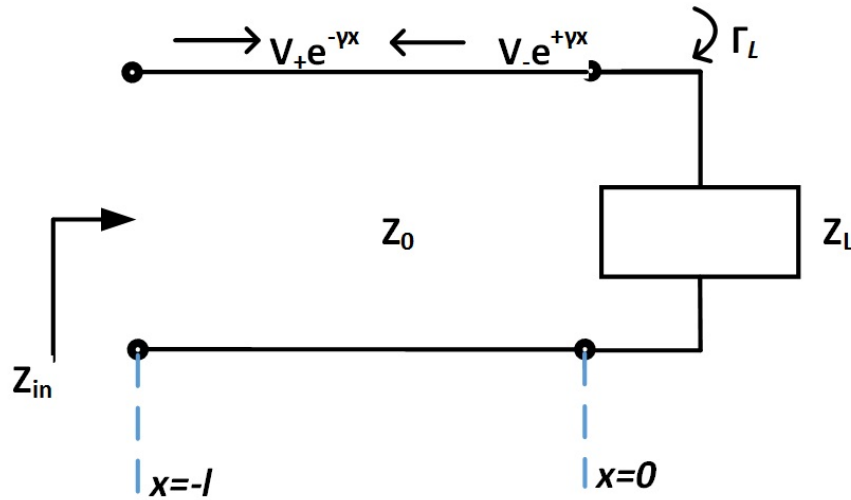
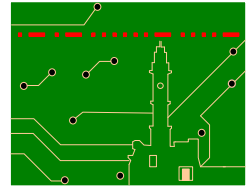


$$Z_{in} = Z_0 \frac{Z_L + Z_0 \tanh \gamma l}{Z_0 + Z_L \tanh \gamma l}$$

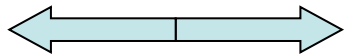
$$\sinh x = \frac{1}{2}(e^x - e^{-x})$$

$$\cosh x = \frac{1}{2}(e^x + e^{-x})$$

Γραμμή Μεταφοράς: Ισχύς στο φορτίο



Ανακλώμενη Ισχύς Εκπεμπόμενη Ισχύς



➤ Γραμμή χωρίς απώλειες: $\alpha=0 \Rightarrow$

$$\gamma = j\beta$$

$$Z_{in} = Z_0 \frac{Z_L + jZ_0 \tan \beta l}{Z_0 + jZ_L \tan \beta l}$$

$$= Z_{in}(l, f, Z_L, Z_0)$$

$$\text{Incident power} = P_{in} = \frac{|V_+|^2}{Z_0}$$

$$\text{Reflected power} = P_r = \frac{|V_-|^2}{Z_0}$$

➤ Ισχύς στο φορτίο ($x=0$):

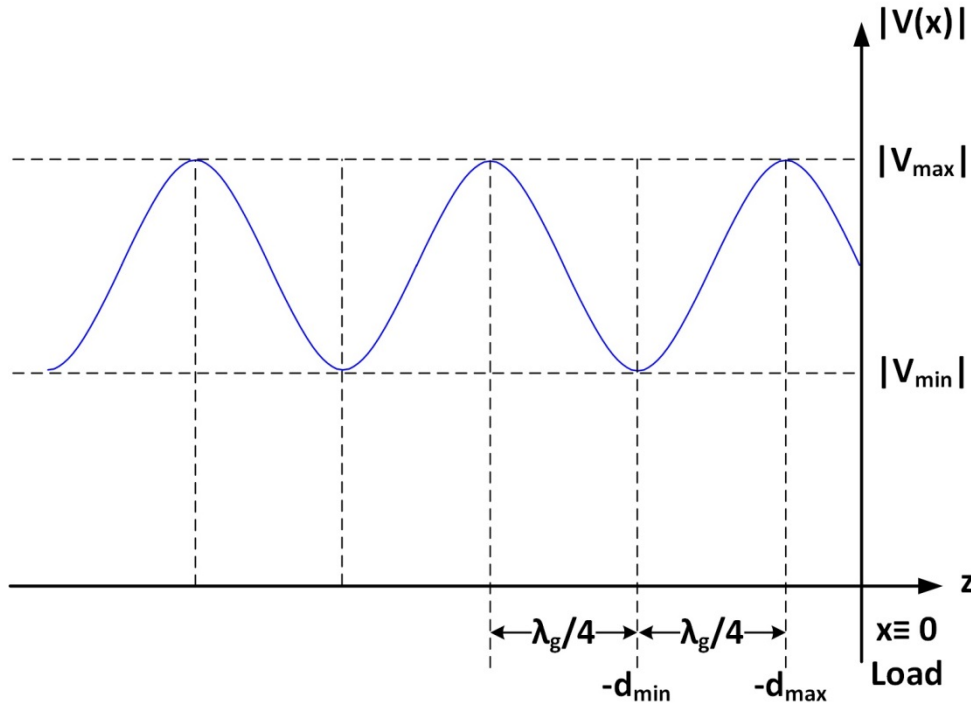
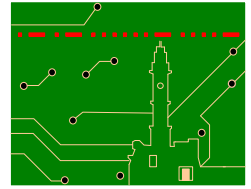
$$= \frac{|V_+|^2 |\Gamma_L|^2}{Z_0} = |\Gamma_L|^2 P_{in}$$

$$\text{Transmitted power} = P_t = P_{in} - P_r$$

$$= (1 - |\Gamma_L|^2) P_{in}$$

$$\text{➤ } Z_{in}(x=-\lambda_g/2) = Z_L, Z_{in}(x=-\lambda_g/4) = Z_0^2/Z_L$$

Γραμμή χωρίς απώλειες: Λόγος Στάσιμου Κύματος Τάσεων (Voltage Standing Wave Ratio - VSWR)



$$V(x) = V_+ e^{-j\beta x} + V_- e^{j\beta x}$$

$$= V_+ e^{-j\beta x} (1 + \Gamma_L e^{2j\beta x})$$



$$\Gamma_L = |\Gamma_L| e^{j\phi}$$

$$\text{VSWR} = \frac{|V_{\max}|}{|V_{\min}|}$$



$$\text{VSWR} = (1 + |\Gamma_L|) / (1 - |\Gamma_L|)$$

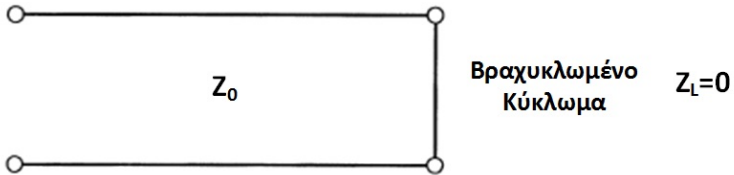
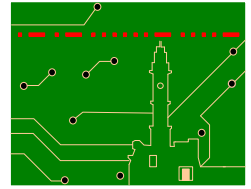


$$|\Gamma_L| = \frac{\text{VSWR} - 1}{\text{VSWR} + 1} = |\Gamma(x)|$$

$$|V(x)| = |V_+| \left[(1 + |\Gamma_L|)^2 - 4|\Gamma_L| \sin^2 \left(\beta x + \frac{1}{2} \phi \right) \right]^{1/2}$$

➤ Τάση $|V(x)|$ περιοδική με περίοδο $\lambda_g/2 = \pi/\beta$

Παράδειγμα Γραμμής Μεταφοράς: Βραχυκύκλωμα



$$Z_{in} = Z_0 \frac{Z_L + jZ_0 \tan \beta l}{Z_0 + jZ_L \tan \beta l}$$

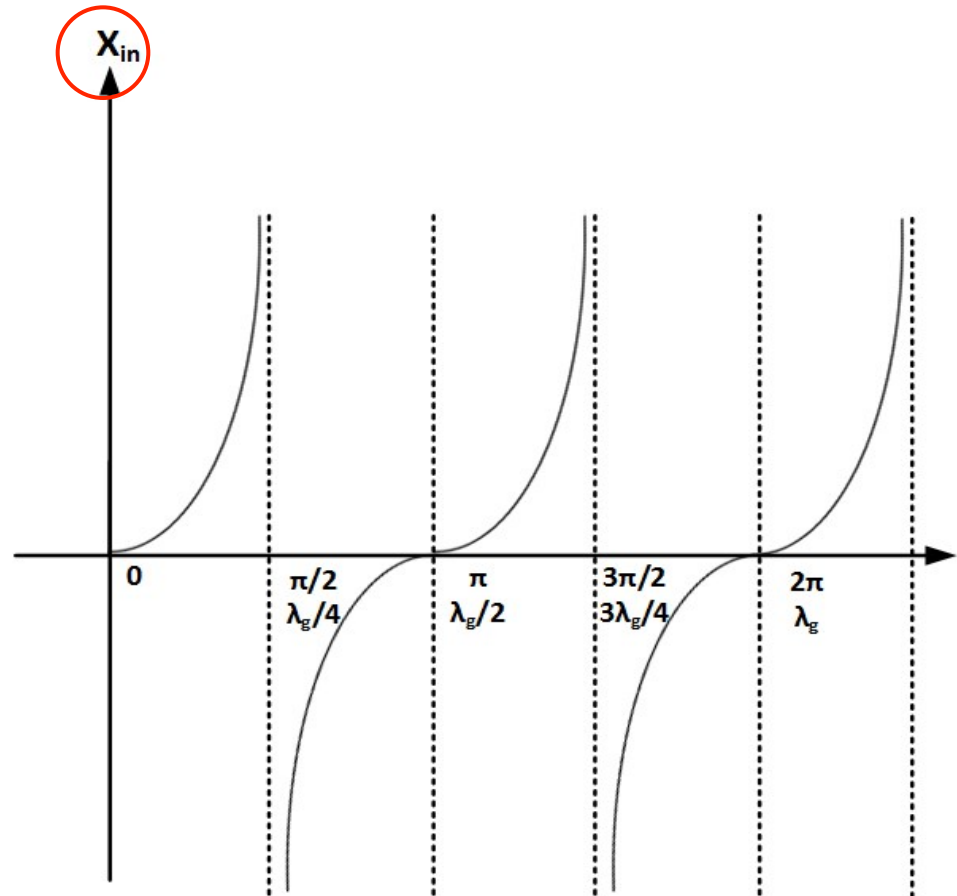
$$= jZ_0 \tan \beta l = jX_n$$

$$\Gamma_L = Z_0 \frac{Z_L - Z_0}{Z_0 + Z_L} = -1$$

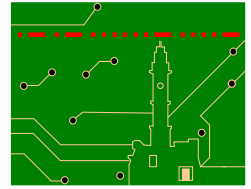
$$VSRW = \frac{1 + |\Gamma_L|}{1 - |\Gamma_L|} = \infty$$

$$\text{Reflected power} = |\Gamma_L|^2 P_{in} = P_{in}$$

$$\text{Transmitted power} = (1 - |\Gamma_L|^2) P_{in} = 0$$



Σύστημα ως Φορτίο: Δίκτυο 2 θυρών (2-port Network)



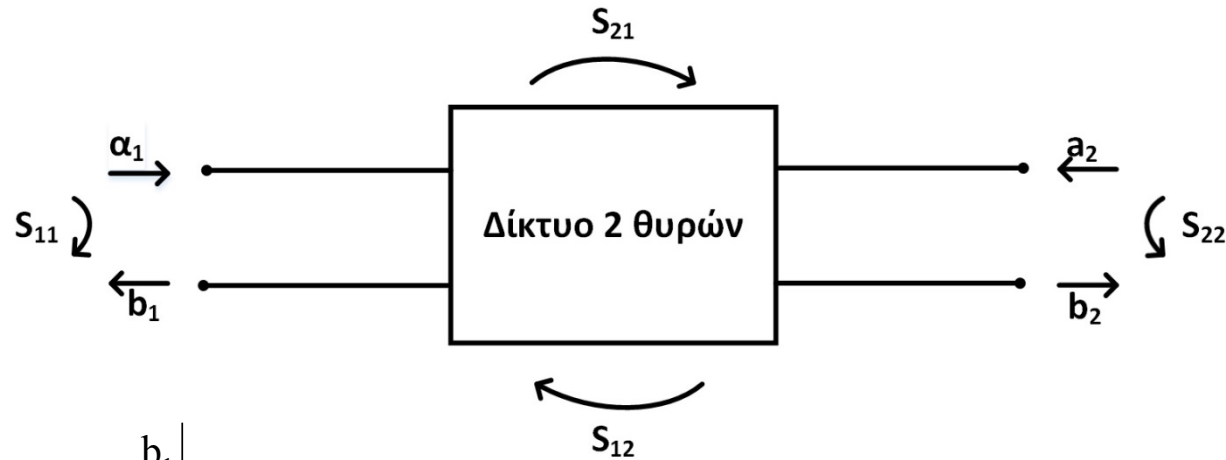
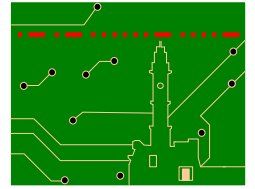
$$\text{Return loss} = \text{RL} = 10 \log \frac{P_{\text{in}}}{P_r} \Rightarrow \text{RL} = -20 \log |\Gamma_L|$$

$$\text{Insertion loss} = \text{IL} = 10 \log \frac{P_{\text{in}}}{P_t}$$

Γνωστό και ως εξασθένιση

- Προσοχή: κάποιοι κατασκευαστές αναφέρουν ως RL το $+20 \log |\Gamma_L|$
- Πώς μετράμε αυτές τις ποσότητες?

Παράμετροι Σκέδασης σε δίκτυο 2 θυρών



$$b_1 = S_{11}a_1 + S_{12}a_2$$

$$b_2 = S_{21}a_1 + S_{22}a_2$$

$$S_{11} = \left. \frac{b_1}{a_1} \right|_{a_2=0} = \Gamma_1 = \text{reflection coefficient at port 1 with } a_2 = 0$$

$$S_{21} = \left. \frac{b_2}{a_1} \right|_{a_2=0} = T_{21} = \text{transmission coefficient from port 1 to 2 with } a_2 = 0$$

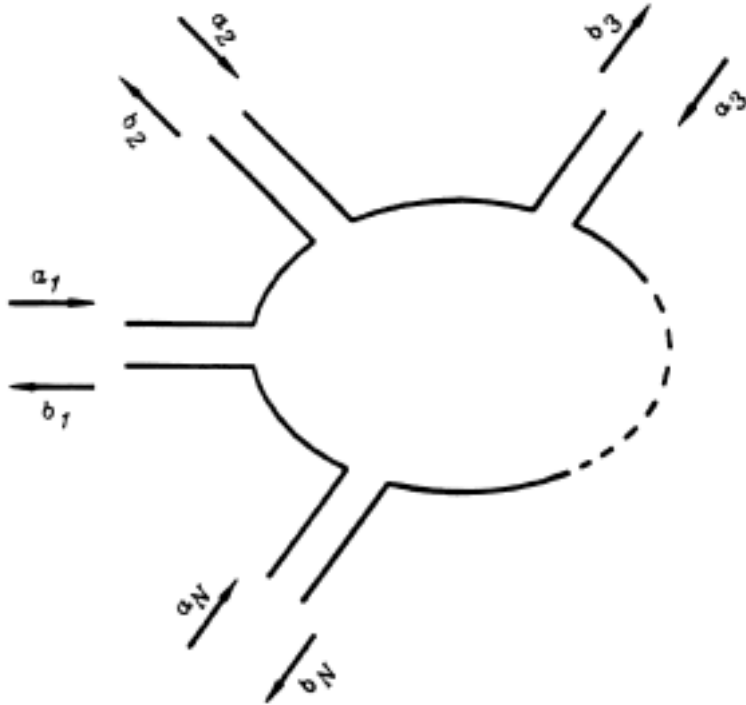
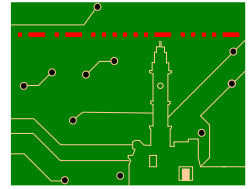
$$S_{22} = \left. \frac{b_2}{a_2} \right|_{a_1=0} = \Gamma_2 = \text{reflection coefficient at port 2 with } a_1 = 0$$

$$S_{12} = \left. \frac{b_1}{a_2} \right|_{a_1=0} = T_{12} = \text{transmission coefficient from port 2 to 1 with } a_1 = 0$$

$$RL = 20 \log \left| \frac{a_1}{b_1} \right| = 20 \log \left| \frac{1}{S_{11}} \right| \text{ (dB)}$$

$$IL = 20 \log \left| \frac{a_1}{b_2} \right| = 20 \log \left| \frac{1}{S_{21}} \right| \text{ (dB)}$$

Παράμετροι Σκέδασης σε δίκτυο N θυρών



$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ \vdots \\ b_N \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & \dots & S_{1N} \\ S_{21} & S_{22} & S_{23} & \dots & S_{2N} \\ \vdots & \vdots & \vdots & \dots & \vdots \\ S_{N1} & S_{N2} & S_{N3} & \dots & S_{NN} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ \vdots \\ a_N \end{bmatrix}$$

➤ Ιδιότητες Παραμέτρων Σκέδασης:

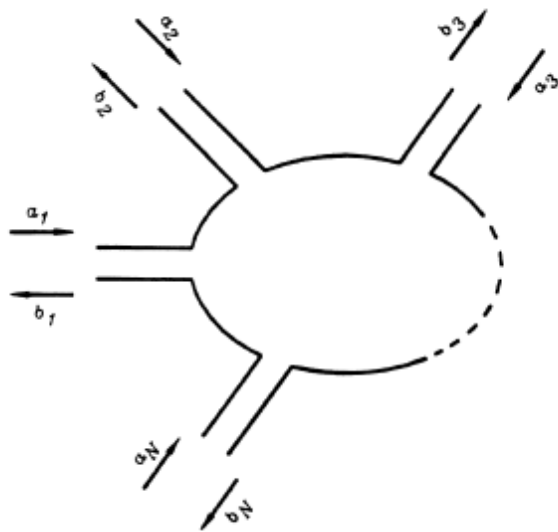
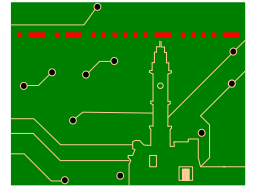
1. For any matched port i , $S_{ii} = 0$.
2. For a reciprocal network, $S_{nm} = S_{mn}$.
3. For a passive circuit, $|S_{mn}| \leq 1$.

Μόνο για δίκτυα χωρίς απώλειες
(Διατήρηση Ισχύος):

$$|S_{1i}|^2 + |S_{2i}|^2 + |S_{3i}|^2 + \dots + |S_{ii}|^2 + \dots + |S_{Ni}|^2 = 1$$

$$\sum_{n=1}^N |S_{ni}|^2 = \sum_{n=1}^N S_{ni} S_{ni}^* = 1$$

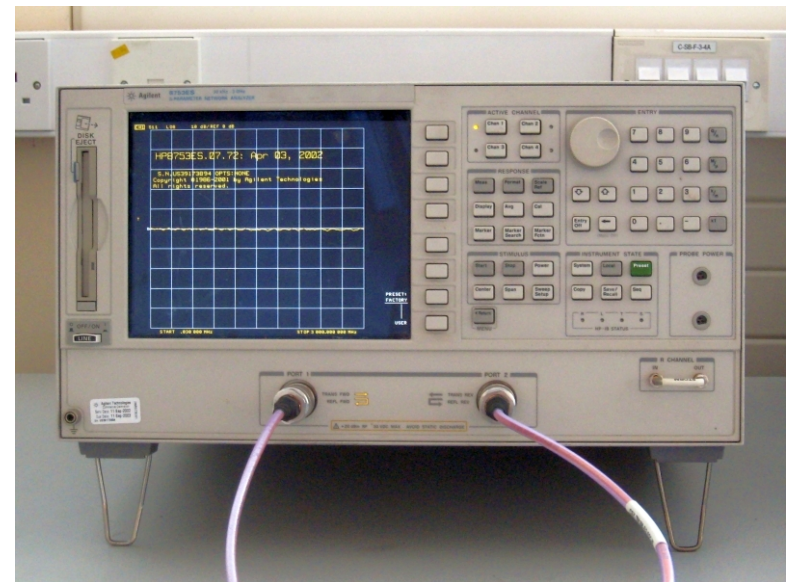
Παράμετροι Σκέδασης σε δίκτυο N θυρών (2)

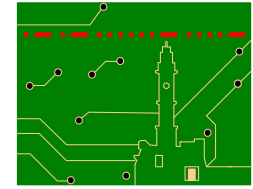


$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ \vdots \\ b_N \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & \cdots & S_{1N} \\ S_{21} & S_{22} & S_{23} & \cdots & S_{2N} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ S_{N1} & S_{N2} & S_{N3} & \cdots & S_{NN} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ \vdots \\ a_N \end{bmatrix}$$

➤ Πώς μετράμε αυτές τις ποσότητες?

Δικτυακός Αναλυτής
(Network Analyzer)





Διάγραμμα Smith

$$\bar{Z}(x) = \frac{Z(x)}{Z_0} = \frac{1 + \Gamma(x)}{1 - \Gamma(x)}$$

$$\Gamma(x) = \Gamma_r(x) + j\Gamma_i(x)$$



$$\bar{R}(x) + j\bar{X}(x) = \frac{1 + \Gamma_r(x) + j\Gamma_i(x)}{1 - \Gamma_r(x) - j\Gamma_i(x)}$$



$$\left(\Gamma_r - \frac{\bar{R}}{1 + \bar{R}} \right)^2 + \Gamma_i^2 = \left(\frac{1}{1 + \bar{R}} \right)^2$$

Constant R Circle

$$(\Gamma_r - 1)^2 + \left(\Gamma_r - \frac{1}{\bar{X}} \right)^2 = \left(\frac{1}{\bar{X}} \right)^2$$

Constant X Circle

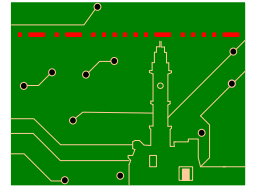
$$\Gamma(x) = \frac{\text{reflected } V(x)}{\text{incident } V(x)} = \frac{V_- e^{\gamma x}}{V_+ e^{-\gamma x}} = \frac{V_-}{V_+} e^{2\gamma x}$$

$$\Gamma_L = \frac{V_-}{V_+} = \Gamma(0) \quad \Rightarrow \quad \Gamma(x) = \Gamma_L e^{2\gamma x} = \Gamma_L e^{j2\beta x}$$

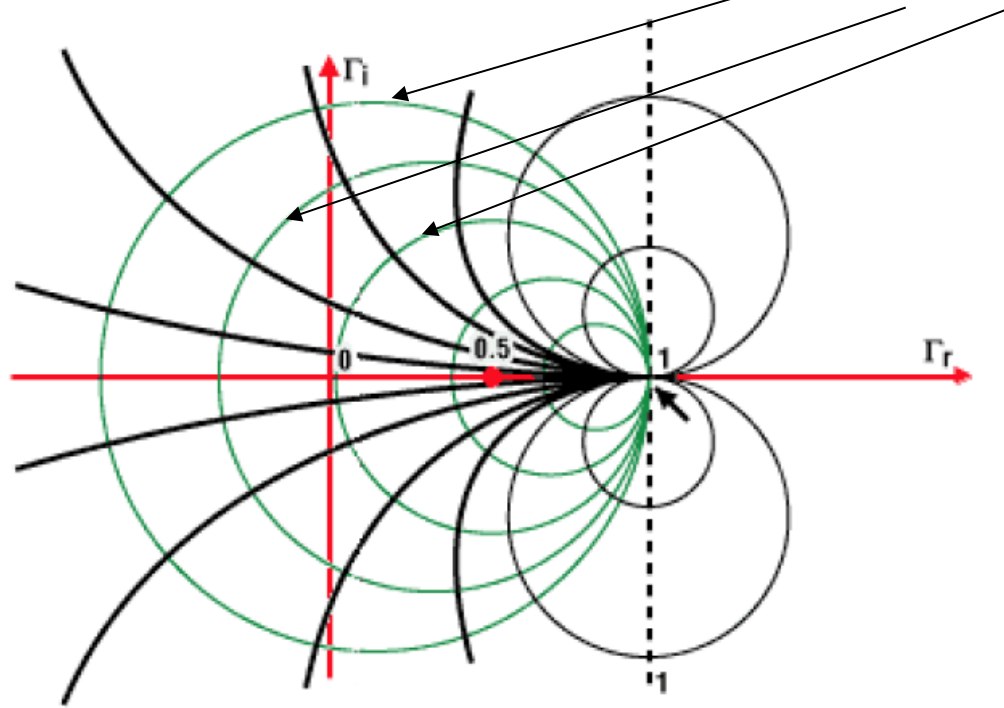
Πολλαπλασιάζοντας αριθμ./παρονομ. με $1 - \Gamma_r + j\Gamma_i$

➤ Διάγραμμα Smith = διάγραμμα στο μιγαδικό επίπεδο του διγραμμικού (bilinear) μετασχηματισμού μεταξύ Z/Z_0 και αντίστοιχου Γ .

Παράδειγμα διαγράμματος Smith



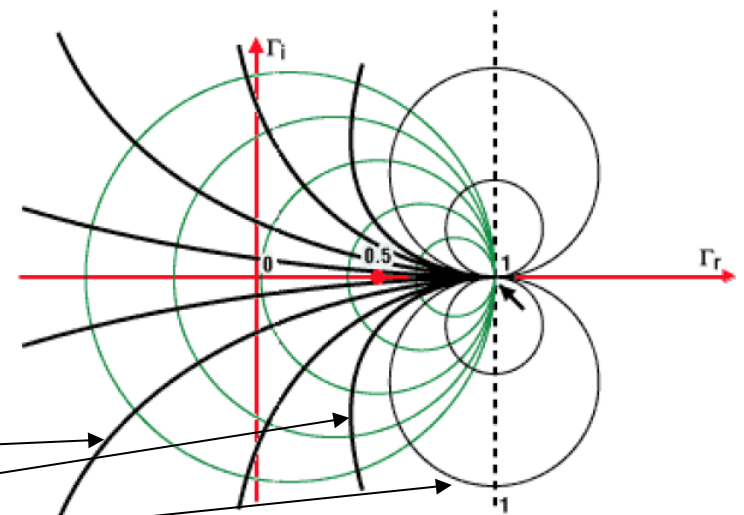
Κύκλος σταθερού R



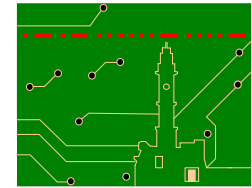
$$\left(\Gamma_r - \frac{\bar{R}}{1 + \bar{R}}\right)^2 + \Gamma_i^2 = \left(\frac{1}{1 + \bar{R}}\right)^2$$

$$(\Gamma_r - 1)^2 + \left(\Gamma_r - \frac{1}{\bar{X}}\right)^2 = \left(\frac{1}{\bar{X}}\right)^2$$

Κύκλος σταθερού X



Διάγραμμα Smith (2)



➤ Γραμμή χωρίς απώλειες:



$$\Gamma(x) = \Gamma_L e^{2\gamma x} = \Gamma_L e^{j2\beta x}$$

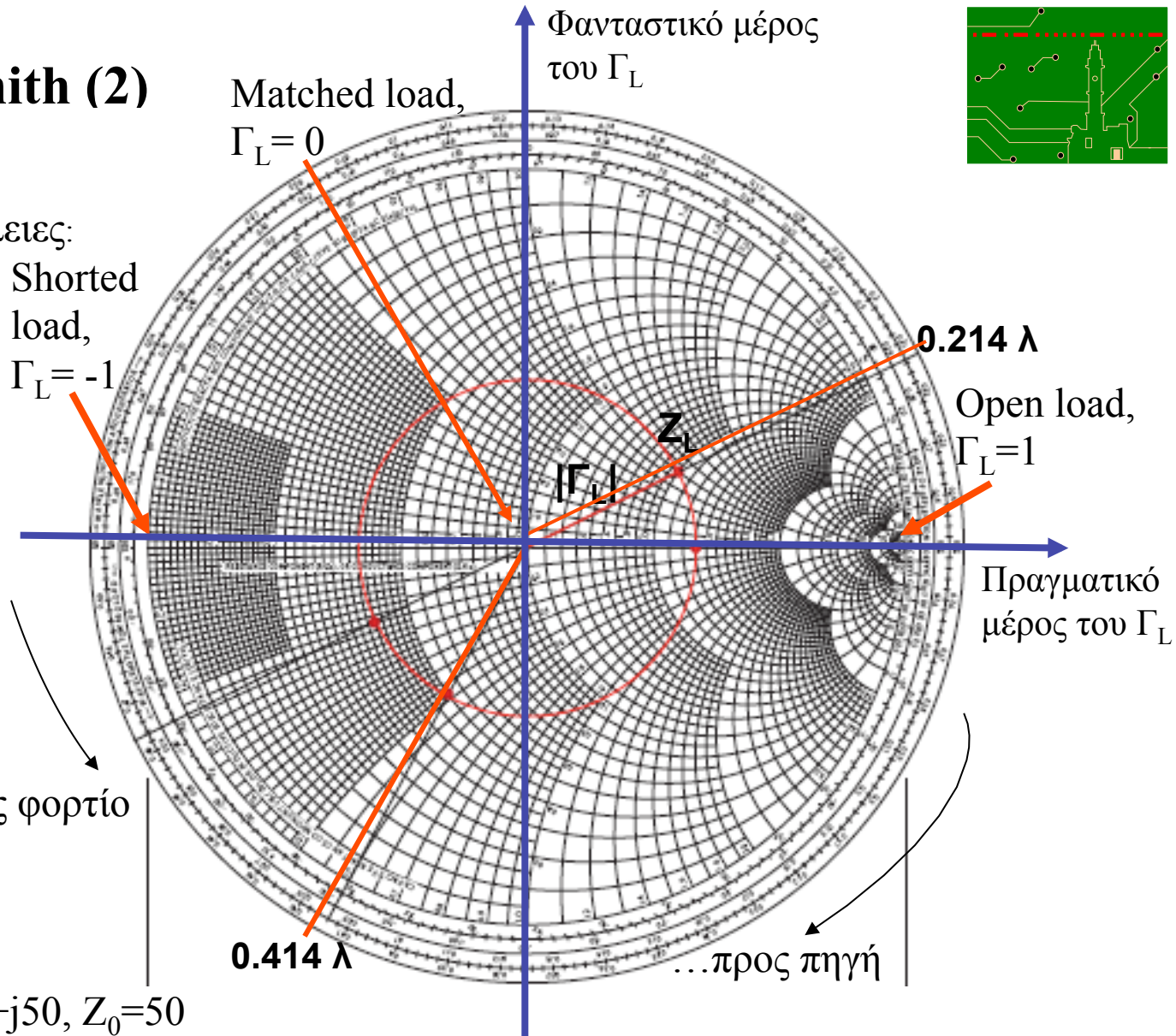


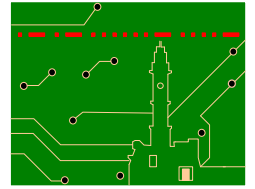
@ Απόσταση x
από φορτίο: μόνο
η φάση αλλάζει,
όχι το πλάτος!

...προς φορτίο

Παράδειγμα: $Z_L = 100 + j50$, $Z_0 = 50$

Παράδειγμα: $\Gamma_L = 0.447 \angle 27^\circ$





Υπολογισμοί παραδείγματος

$$Z_L = 100 + j50$$

$$\bar{Z}_L = \frac{Z_L}{Z_0} = 2 + j$$

$$\bar{Z}_L = \frac{Z_L - Z_0}{Z_L + Z_0} = \frac{\bar{Z}_L - 1}{\bar{Z}_L + 1} = \frac{1 + j}{3 + j} = 0.4 + 0.2j$$
$$= 0.447 \angle 27^\circ$$

$$\Gamma_L = 0.447 \angle 27^\circ$$

$$|\Gamma_L| = 0.447$$

$$\text{VSWR} = \frac{1 + |\Gamma_L|}{1 - |\Gamma_L|} = \frac{1 + 0.447}{1 - 0.447} = 2.62$$

$$\bar{Z}(x) = \frac{Z(x)}{Z_0} = \frac{1 + \Gamma(x)}{1 - \Gamma(x)}$$

$$\bar{Z}_L = 2 + j$$

$$\bar{Y}_L = \frac{1}{\bar{Z}_L} = \frac{1}{2 + j} = 0.4 - j0.2$$

$$\Gamma(\lambda_g / 4) = -\Gamma_L \Rightarrow Z(\lambda_g / 4) / Z_0 = \frac{1 + (-\Gamma_L)}{1 - (-\Gamma_L)} = \frac{Z_0}{Z_L} = \frac{1}{\bar{Z}_L}$$

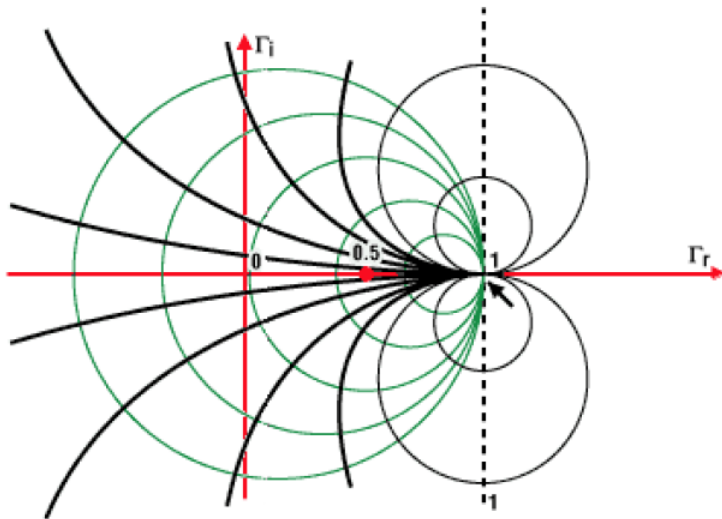
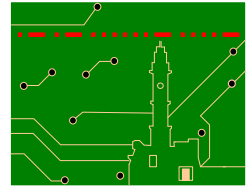
$$\bar{Z}_{in} = Z_0 \frac{Z_L + jZ_0 \tan \beta l}{Z_0 + jZ_L \tan \beta l}$$

$$l = 0.2\lambda_g, \quad \beta l = \frac{2\pi}{\lambda_g} \times 0.2\lambda_g = 0.4\pi$$

$$\tan \beta l = 3.08$$

$$\bar{Z}_{in} = \frac{2 + j + j3.08}{1 + j(2 + j) \times 3.08} = 0.496 - j0.492$$

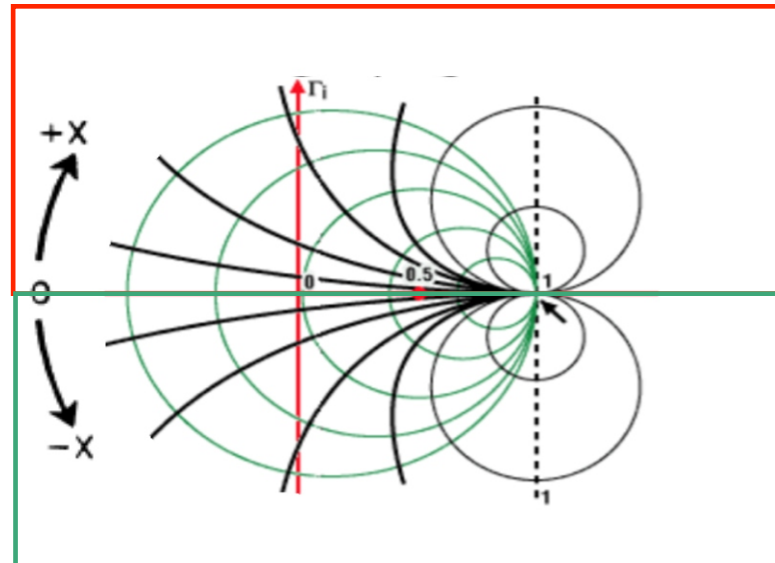
Z-Y Διάγραμμα Smith



$$\begin{aligned} \bar{Z}_{in} \left(l = \frac{\lambda_g}{4} \right) &= \frac{Z_L + jZ_0 \tan \beta l}{Z_0 + jZ_L \tan \beta l} \\ &= \frac{Z_0}{Z_L} = \frac{1}{Z_L} = \bar{Y}_L \end{aligned}$$

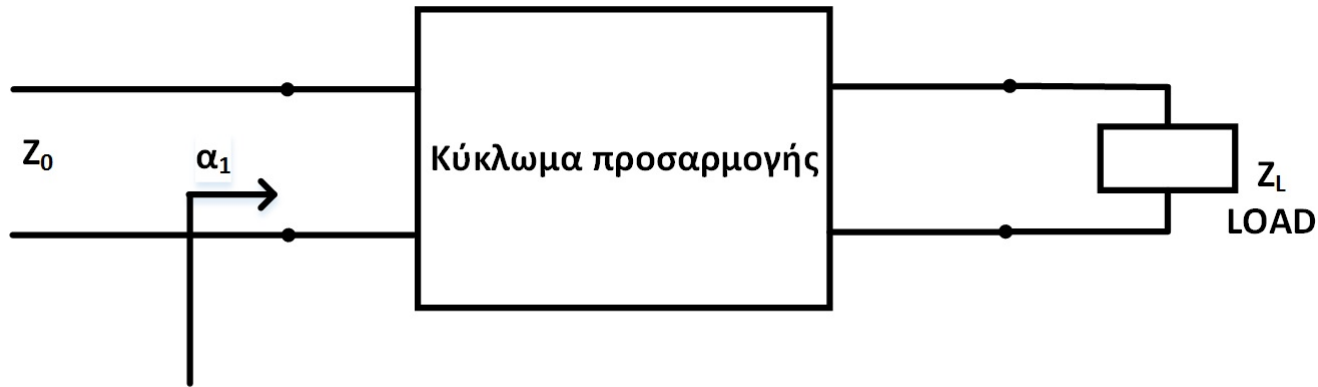
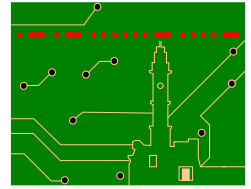
επαγωγικό φορτίο

χωρητικό φορτίο



- Συμμετρικό σημείο του $z=Z/Z_0$ ως προς την αρχή των αξόνων δίνει $1/z = y = Y/Y_0 = Z_0/Z$ (!)
- Σημ.: διαφορά φάσης $\pi =$ κίνηση κατά $\lambda_g/4$ (και όχι $\lambda_g/2$) [γιατί?]

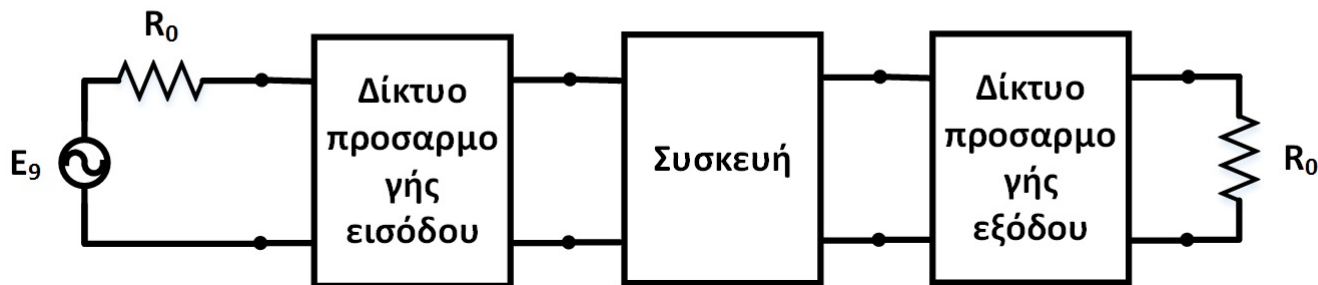
Προσαρμογή εμπέδησης (σύνθετης αντίστασης): μεγιστοποίηση μεταφοράς ισχύος



Θέλουμε $Z_{in} = Z_0$

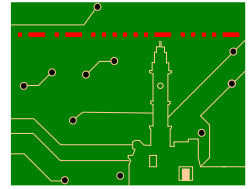
$$\Gamma(x) = 0$$

$$VWSR = 1$$

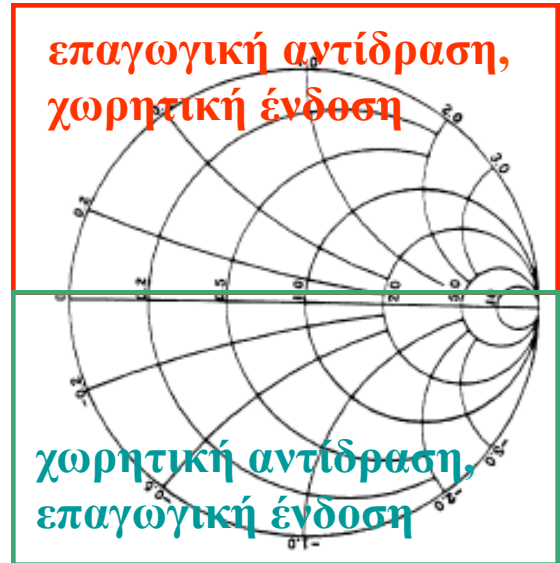


- **2-θυρα συστήματα** απαιτούν προσαρμογή εισόδου και εξόδου για μέγιστη μεταφορά ισχύος (προσαρμογή γραμμής στην εμπέδηση της πηγής και στο φορτίο εξόδου).

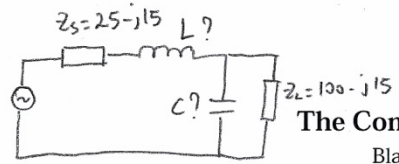
Πρακτικά: δουλεύουμε σε Z-Smith



- Πάνω ημικύκλιο: θετική αντίδραση (reactance) ή ένδοση (susceptance)
- Κάτω ημικύκλιο: αρνητική αντίδραση (reactance) ή ένδοση (susceptance)
- Σημειώνουμε Z/Z_0 όταν προσθέτουμε ένα στοιχείο σε σειρά.
- Σημειώνουμε Z_0/Z όταν προσθέτουμε ένα στοιχείο παράλληλα (δηλ. σημειώνουμε το Z/Z_0 και στην συνέχεια σημειώνουμε το συμμετρικό του ως προς το σημείο (0,0)).
- στον κύκλο σταθερού R, κινούμαστε προς το πάνω ημικύκλιο για θετικό φορτίο (positive reactance ή positive susceptance).
- στον κύκλο σταθερού R, κινούμαστε προς το κάτω ημικύκλιο για αρνητικό φορτίο (negative reactance ή negative susceptance).



Παράδειγμα Προσαρμογής (2)

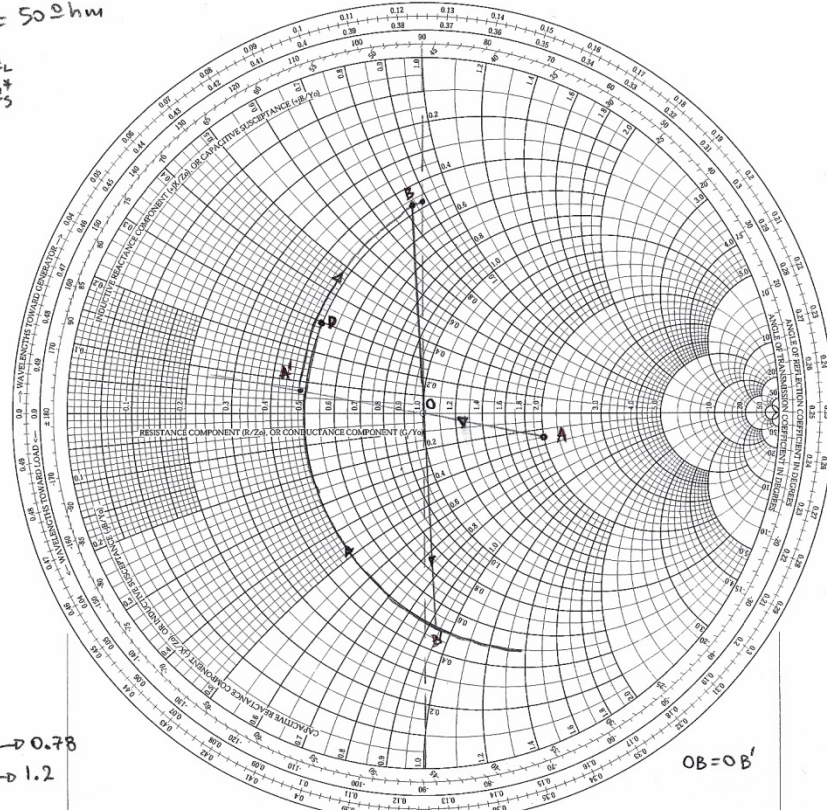


The Complete Smith Chart

Black Magic Design

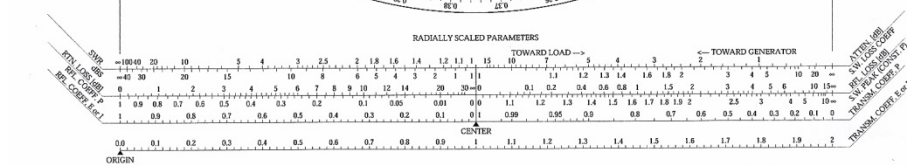
$f = 60 \text{ MHz}$
 $Z_0 = 50 \Omega$

$A: Z_L$
 $D: Z_0^*$



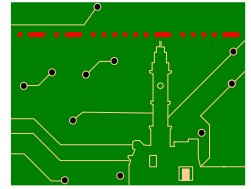
$A'B \rightarrow 0.78$
 $B'D \rightarrow 1.2$

$OB = OB'$



$$\begin{aligned}
 0.78 = R &\Rightarrow 0.78 \cdot Y_0 = C \cdot \omega \\
 1.2 = X &\rightarrow 1.2 \cdot Z_0 = L \cdot \omega \\
 Z_0 &= 50 \Omega \\
 \omega &= 2\pi f = 2\pi \cdot 60 \cdot 10^6
 \end{aligned}
 \quad \left. \vphantom{\begin{aligned} 0.78 = R \\ 1.2 = X \end{aligned}} \right\}
 \begin{aligned}
 C &= 41.4 \text{ pF} \\
 L &= 153 \text{ nH}
 \end{aligned}$$

➤ Παράδειγμα Προσαρμογής με Διάγραμμα Smith!



Ερωτήσεις?

