OPTIMUM DESIGN OF FAST ACTING BROADBAND MULTITHROW DIODE SWITCHES

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This paper utilizes wideband matching theory to derive the maximum bandwidth capabilities of fast-acting, broadband multithrow diode switches, and filter techniques to closely realize them. Using these filter matching techniques, a 1:16 multithrow switch was constructed and evaluated. It achieves less than 1 db insertion loss, 1.3:1 input VSWR and 27 db isolation from dc to 750 mc which agrees closely with the theory. Switching times as small as 40 nsec have been observed. These results represent a significant advancement in the design of fast-acting diode multithrow switches.

The equivalent circuit of a diode at microwave frequencies is well known. The whisker inductance L_W and case capacity C_p are funtions of the diode package whereas the series resistance R_s and zero bias junction capacity C_j are functions of the semiconductor junction. When a forward bias is applied to the junction, the junction capacity is essentially shorted out, producing an on state. When a reverse bias is applied, an off state results where C_j is a function of the bias voltage. For ultra-wideband switches, modes of operation that depend upon resonances between parasitic elements are not useful. To attain maximum bandwidth, it is necessary to use the diode in its normal or d-c mode, and attempt to minimize the effect of the parasitic elements. In the d-c mode a 1:n multithrow switch is formed by connecting n such identical diodes to a common junction. To achieve satisfactory operation as a switch in this mode, the following conditions must be met.

(1) $\left| x_{C_{p_i}} \right| \gg \left| x_{L_{w_i}} \right|$ to prevent parallel resonance

(2) $\left| X_{C_{j_i}} \right| \gg \left| X_{L_{w_i}} \right|$ to prevent series resonance

(3) $\left| X_{C_{j_i}} + C_{p_i} \right| \gg \left| X_{L_{w_i}} + R_{s_i} \right|$ for switching action.

The equivalent circuit of the 1:n switch can then be simplified as shown in Figure 1 where energy is being transferred from the input port to the nth output port and isolated from all the other output n-1 ports. From this equivalent circuit, the maximum bandwidth, maximum isolation, and minimum insertion loss of a 1:n multithrow switch is determined in terms of the diode parameters.

The critical problem in the achievement of the multithrow diode switch is that of matching a junction of n diodes over a broad frequency band. The matching technique must allow power arriving at the junction via the input port to be routed through any forward-biased diode (nth diode) to its adjacent output port without appreciable mismatch due to the other (n-1) reverse-biased diodes. These reverse-biased diodes capacitively shunt the n junction to ground as shown in Figure 1. This shunting effect imposes the basic limitation upon the bandwidth of this device.

The problem of matching an arbitrary load impedance is quite difficult. The solution for a fixed shunt capacitance associated with a load resistance, however, is available and can be applied to this particular circuit. Bode[1] has shown that:

(4) $\log_e \left| \frac{1}{\rho} \right| \leq \frac{\pi}{\omega_B CR}$ where C = shunt capacity
R = load resistance
ρ = input reflection coefficient

over the frequency band $0 - \omega_B$.

If a maximum tolerable input reflection coefficient $\left| \rho_{max} \right|$ is to be permitted in the passband, then the maximum bandwidth will be attained with a matching network whose input reflection coefficient is kept as close to $\left| \rho_{max} \right|$ as possible throughout the passband, and reaches and maintains a value close to unity as near as possible to the edges of the passband. This can be satisfactorily accomplished for the d-c mode multidiode switch by incorporating the shunt capacity into a low-pass filter network as shown in Figure 1. The design of low-pass filters using modern network theory has been adequately treated elsewhere[2], and no attempt will be made to repeat these analyses here. The results of these analyses, however, will be used to derive the performance characteristics of the switch.

From Bode's analysis we have:

(5) $$f_{max} \leq \frac{1}{2R_g C_T \log_e \left| \frac{1}{\rho_{max}} \right|}$$

where

R_g = source impedance

C_T = (n-1) $(C_{p_i} + C_{j_i})$

C_{p_i} = C_p of the diode at the ith off port

C_{j_i} = C_j of the diode at the ith off port

$|\rho_{max}|$ = Absolute value of the maximum tolerable reflection coefficient over the band 0 - f_{max}.

When realization of this maximum bandwidth is accomplished by incorporating the shunt C_T and series L_{w_n} into a low-pass filter, the R_g and $f_{3\ db}$ can be calculated from the following:

(6) $$R_g = q_1 k_{12} \sqrt{\frac{L_{w_n}}{C_T}}$$

where

L_{w_n} = Whisker Inductance of "ON" Diode

$f_{3\ db}$ = frequency at which attenuation of the filter exceeds 3 db.

(7) $$f_{3\ db} = \frac{1}{(C_T L_{w_n})^{1/2}\ k_{12}\ 2\pi}$$

and q_1 and k_{12} are functions of the passband characteristic (linear phase, maximum flat or equal ripple) and the number of reactive elements. Although elegant closed form expressions for these constants are available, they are more readily used in tabular form[2].

The degree to which these various low-pass filters realize the theoretical Bode matching criteria can now be calculated. By substituting R_g into Bode's equation

(8) $$f_{max} \leq \frac{1}{2q_1 k_{12}(L_{w_n} C_T)^{1/2} \log_e \left|\frac{1}{\rho_{max}}\right|}$$ where f_{max} = Bode maximum frequency for given $|\rho_{max}|$.

From modern filter theory,

(9) $$f_{realized} = f_{3\ db}\ C = \frac{C}{(C_T L_{w_n})^{1/2} k_{12} 2\pi}$$

$f_{realized}$ is the frequency at which reflection coefficient of the filter exceeds $|\rho_{max}|$ and the constant C is a function of passband shape and gives the frequency at which the filter reflection coefficient exceeds $|\rho_{max}|$ instead of the conventional 3 db attenuation point. Using these equations, f_{max} and $f_{realized}$ can now be tabulated, normalized to $(C_T L_{w_n})^{1/2}$, as a function of passband ripple and number of reactive elements used in the filter.

TABLE 1

Passband Tolerance	3 Pole Network f_{n} max	3 Pole Network f_{n} realized	3 Pole Network Per cent realized	6 Pole Network f_{n} max	6 Pole Network f_{n} realized	6 Pole Network Per cent realized
0 db	---	.225*	---	---	.136*	---
0.1 db	.28	.172	61	,295	.202	68
1.0 db	.44	.227	51	.445	.248	56
3.0 db	.675	.25	37	.69	.260	38

$f = f_n \times \left(\frac{1}{(L_w C_T)^{1/2}}\right)$

* 3 db cut off

From the table it can be seen that even simple 3 pole low-pass filter matching realizes a good percentage of the maximum bandwidth given by the Bode equation. The table can therefore be used to predict the Bode maximum and realizable bandwidth for a multithrow switch of given passband tolerance in terms of the diode parameters L_w and C_T. Accurate plots of both skirt and passband characteristic are readily found in the literature.[2]

The isolation from an off port to the input for a "Tee" section filter matched switch is given in the following:

$$(10) \quad \text{Isolation} = (n-1) \frac{R_g}{R_{L_T}} \left[\frac{\left(\frac{\omega^2}{2} - \omega_o^2\right)^2 L_{W_n}^2}{\omega^2 R_g^2} + \frac{1}{4} \left(1 + \frac{2R_{L_T}}{R_g}\right)^2 \right]$$

$$\text{where } R_{L_T} = \frac{R_{S_i}}{(n-1)}$$

Since the filter matching technique previously described reduces the input VSWR to a small value, the insertion loss in the passband is wholly dissipative and is caused by circuit dissipation, diode dissipation and power lost to the off ports. To determine the total dissipative insertion loss, each of these factors has been analyzed separately and their total added. The total dissipative insertion loss $\left(\frac{P_{dissipated}}{P_{available}}\right)$ is equal to the following:

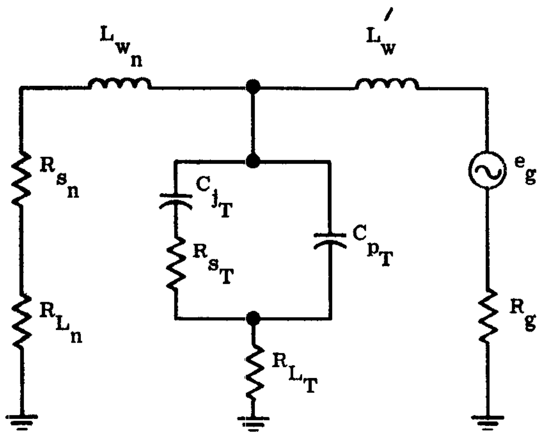
$$(11) \quad \frac{R_{S_n}}{R_{L_n}} + \left[1 + \left(\frac{C_{j_i}}{C_{j_i} + C_{p_i}}\right)^2 \frac{R_{S_i}}{R_{L_i}} \right] \left[\frac{R_g}{R_{L_T}} \left[\frac{\left(\frac{\omega^2}{2} - \omega_o^2\right)^2 L_{W_n}^2}{\omega^2 R_g^2} + \frac{1}{4} \left(1 + \frac{2R_{L_T}}{R_g}\right)^2 \right] \right]^{-1}$$

The total attenuation versus frequency characteristic of the filter-matched switches may be obtained by adding these dissipative losses to the lossless filter attenuation curves described in the bandwidth discussion.

A 1:16 diode switch operating in the d-c mode and utilizing the filter structure realization was designed and built for operation in the frequency range 0 - 800 mc. A three-pole low-pass "Tee" section was employed. The theoretical values of insertion loss were calculated for this case and are presented in Figure 2 together with the values observed during the evaluation of the model. The theoretically predicted performance agrees closely with the actual measured performance. This indicates that the equivalent circuit representation of the switch is correct and the approximations made for the d-c mode conditions are justified. The application of this optimum design technique to any 1:n diode multithrow switch using any diode which satisfies the d-c mode conditions and should therefore result in the practical realization of the theoretical values.

[1] Bode, "Network Analyses and Feedback Amplifier Design," Sec 16.3, New York, VanNostrand, 1945.

[2] Reference Data for Radio Engineers, International Telephone and Telegraph Corp., copyright 1956.



L_{w_n} = "ON" Diode whisker inductance

R_{s_n} = "ON" Diode series resistance

R_{L_n} = Load connected to ON diode

$$C_{j_t} = \sum_{1}^{n-1} C_j$$

$$C_{p_t} = \sum_{1}^{n-1} C_p$$

$$R_{s_t} = \frac{R_{s_n}}{n-1}$$

$$R_{l_t} = \frac{R_{l_n}}{n-1}$$

L_w' ADDITION MATCHING INDUCTOR TO PRODUCE TEE SECTION

Figure 1. Tee Section Matched 1:n Multithrow Diode Switch

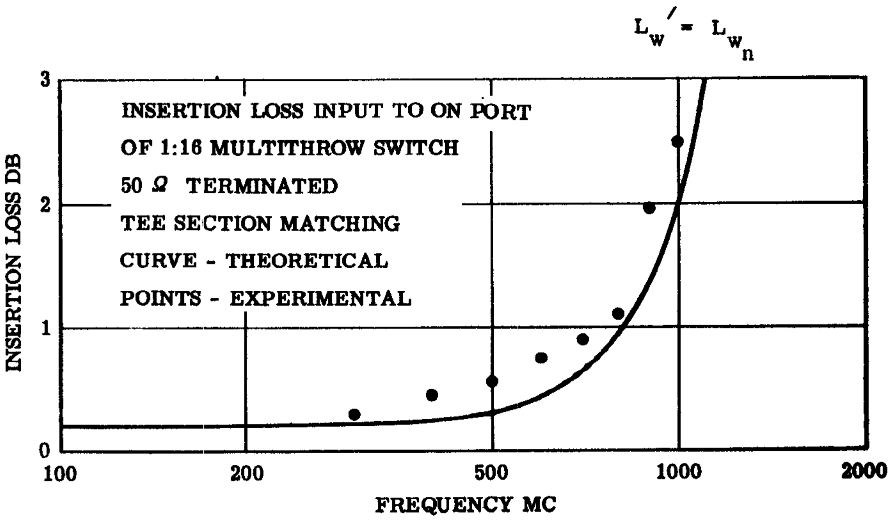


Figure 2. Insertion Loss of 1:16 Diode Switch

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