THE DESIGN AND ANALYSIS OF MULTI-MEGAWATT DISTRIBUTED SINGLE POLE DOUBLE THROW (SPDT) MICROWAVE SWITCHES

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ABSTRACT

We present a design methodology and analysis for an SPDT switch that is capable of handling hundreds of megawatts of power at X-band. The switch is designed for application in high power rf systems in particular future Linear Colliders [1]. In these systems switching need to be fast in one direction only. We use this to our advantage to reach a design for a super high power switch. In our analysis we treat the problem from an abstract point of view. We introduce a unified analysis for the microwave circuits irrespective of the switching elements. The analysis is, then, suitable for different kinds of switching elements such as photoconductrs, PIN diodes, and plasma discharge in low-pressure gases.

INTRODUCTION

The basic switch would have to have at least three ports. One for the incoming rf signal, port 1, and two for the out going signal, ports 2 and 3. The most straightforward idea is to put two switches that are always working in a complimentary mode, that is, when the first is off the second is on and visa versa. This way the power flow can be controlled from port 1 to either port 2 or 3. In this case we used two switches, and each switch had to control the flow of all the power. An alternative to this is the *dual mode rf switch* shown in Fig. 1.

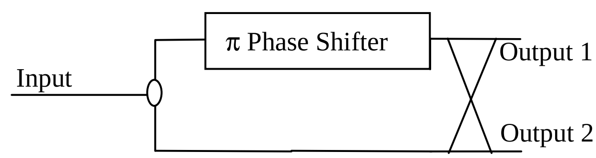

Figure 1. Schematic Diagram of a dual mode SPDT

The power is split first between two ports and then combined again into a 3dB hybrid. A switch put on one of the arms connecting the splitter to the hybrid can switch the phase of the rf signal in that arm by a 180 degrees thus steering the rf to a particular port at the output of the hybrid. In this scheme the switch has to handle only half the power. The implementation of this switch can take different forms. Any structure that supports two different coupled modes can be used to implement the switch.

THE DISTRIBUTED PHASE SHIFTER

The phase shifting element in one of the arms can be considered as a series of *symmetric* three-port elements; see Fig. 2. Each element is a basic *loss-less* three-port device with two similar ports, namely, port 1 and port 2. The

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third port is terminated so that all the scattered power from that port is completely reflected.

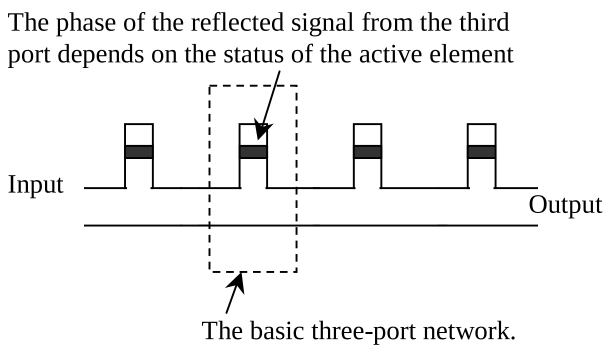

Figure 2. A series of elements composes the phase shifting device. The number of these elements is not limited to 4. In the limiting case it can be viewed as corrugated guide with an active element in each corrugation.

However, the phase of the reflected signal from the third port can be changed actively. The active element at the third port is simply a medium that changes its properties from a dielectric like material to a conductor like martial in a controlled manner. One can use bulk phenomenon in pure semi-conductors [2], a PIN diode structure or a plasma discharge in a gas [3]. Thus one can shift the plane of the reflected signal from a static reflector behind the active element to a plane just in front of the active element.

One can show that there is always an angle, for the reflection coefficient in the third port, which makes the device completely matched. By changing this angle and placing the elements with proper spacing one can also achieve matching conditions, however, with a total different phase shift through the elements. Under the constraints of a minimum break down fields for the elements, a reasonable switching time, and losses in the elements in both the *off* and *on* state, we derive expressions for the optimal switch design. The design is a function of the number of elements, the size and mode of operation in the third port of each element, and the parameters that specify the properties of the three port networks.

SYNTHESIS OF THE π PHASE SHIFTER USING A SERIES OF SYMMETRIC THREE PORT NETWORKS

For any loss-less and reciprocal three-port network the scattering matrix is unitary and symmetric. By imposing these two conditions on the scattering matrix $\underline{\underline{S}}$ of our device and at the same time taking into account the symmetry between port 1 and port 2; at some reference planes, one can write:

$$\underline{\underline{S}} = \begin{pmatrix} \frac{e^{j\phi}-\cos\theta}{2} & \frac{-e^{j\phi}-\cos\theta}{2} & \frac{\sin\theta}{\sqrt{2}} \\ \frac{-e^{j\phi}-\cos\theta}{2} & \frac{e^{j\phi}-\cos\theta}{2} & \frac{\sin\theta}{\sqrt{2}} \\ \frac{\sin\theta}{\sqrt{2}} & \frac{\sin\theta}{\sqrt{2}} & \cos\theta \end{pmatrix}. \quad (1)$$

Indeed, with the proper choice of the reference planes, this expression is quite general for any symmetric three-port network. The scattering matrix properties are determined completely with only two parameters: θ and ϕ. The scattered rf signals $\underline{V}^-$ are related to the incident rf signals $\underline{V}^+$ by

$$\underline{V}^- = \underline{\underline{S}}\underline{V}^+; \quad (2)$$

where $V_i^{\pm}$ represents the incident/reflected rf signal from the *i*th port. We terminate the third port so that all the scattered power from that port is completely reflected; i.e.,

$$V_3^+ = V_3^- e^{j\psi}. \quad (3)$$

The resultant, symmetric, two-port network, then, has the following scattering matrix parameters:

$$S_{11} = S_{22} = \cos\left(\frac{\zeta-\phi}{2}\right) e^{j\left(\frac{\phi}{2}+\frac{\zeta}{2}+\alpha\right)}, \quad (4)$$

$$S_{12} = S_{21} = j\sin\left(\frac{\zeta-\phi}{2}\right) e^{j\left(\frac{\phi}{2}+\frac{\zeta}{2}+\alpha\right)}; \quad (5)$$

where the angle ζ is given by

$$e^{j\zeta} = \frac{\cos\theta - e^{j\psi}}{\cos\theta e^{j\psi} - 1}, \qquad (6)$$

and α is an arbitrary angle added to (4) and (5) so that the reference planes can be chosen at will. The signal level in the third arm is given by,

$$\left|V_3^+\right|^2 = \left|V_3^-\right|^2 = \frac{\sin^2\theta}{3 - 4\cos\theta\cos\psi + \cos 2\theta}\left|V_1^+ + V_2^+\right|^2 \qquad (7)$$

A series of these two port networks can be cascaded together to produce the desired phase shifter. When the active element in each of the three port networks is not excited the reflection coefficient from that port is $e^{j\psi_0}$. We choose the angle ψ_0 such that each of the three-port networks is matched by itself, i.e., $S_{11} = S_{22} = 0$, and, in that case, $S_{12} = S_{11} = e^{j(\phi+\alpha+\pi)}$. Once the active element is excited the angle of the reflection coefficient in the third arm changes to become ψ_1. We choose ψ_1 and the angle α so that the train of three port networks is matched and the total phase shift across the train differs by π when the angle of the third arm reflection changes from ψ_0 to ψ_1.

The train of three port networks can be viewed as a periodic structure. This periodic structure is inserted between two transmission lines with different characteristic impedance than that of the transmission line formed by the periodic structure. A matching condition occurs when the total phase shift across the structure is π, i.e., the periodic structure represents a half wavelength transmission line transformer. In this case the phase shift across the periodic structure should go to zero as $\psi \rightarrow \psi_0$. This defines the proper choice of the reference planes, hence,

$$\alpha = \pi - \phi \pm \frac{2\pi}{n}; \qquad (8)$$

where n is the number of three port networks in the periodic structure.

Substituting from (8) into (4) and (5) we get the scattering matrix of each element of the periodic structure. We then use this scattering matrix to produce the transfer matrix A [4]. To make the total phase shift across the structure become π, A should satisfy, $A^n = -I$; where I is the identity matrix. Hence, the eigen values of A are $e^{\pm j\frac{\pi}{n}}$. The sufficient and necessary condition for A to have these eigen values is

$$\zeta_1 = \phi \pm 2\tan^{-1}\left(\frac{2\cos\frac{\pi}{2n}\cos\frac{\pi}{n}}{\sin\frac{3\pi}{n}}\right); \qquad (9)$$

where $\zeta \rightarrow \zeta_1$ as $\psi \rightarrow \psi_1$. Then the difference between the two angles $\Delta\psi = \psi_1 - \psi_0$ is given by,

$$e^{j\Delta\psi} = \frac{\left(e^{j\zeta_1} + \cos\theta\right)\left(1 - e^{j\phi}\cos\theta\right)}{\left(e^{j\phi} + \cos\theta\right)\left(1 - e^{j\zeta_1}\cos\theta\right)}. \qquad (10)$$

We then, using (7), can show that the electric field present at the active element when $\psi \rightarrow \psi_0$ is

$$E_{\max} = 2\left(\frac{1 + \cos^2\theta - 2\cos\phi\cos\theta}{\sin^2\theta}\right)^{\frac{1}{2}} \times \left|\sin\frac{\Delta\psi}{2}\right|\left(\frac{P_{in}Z_3}{A_3 G_3}\right)^{1/2}; \qquad (11)$$

where P_{in} is the constant level input power, Z_3 is the wave impedance of the mode excited in the waveguide that forms the third arm, A_3 is the cross sectional area of that guide, and G_3 is a geometrical factors that depends on the mode and the waveguide shape of the third arm.

When the switch is turned *on*, i.e., $\psi \rightarrow \psi_1$, the losses P_l in the active element is given by

$$P_l = \frac{1 + \cos^2\theta + 2\cos\zeta_1\cos\theta}{2\sin^2\theta}\frac{R_s}{Z_3}\left|V_1^+ + V_2^+\right|^2; \qquad (12)$$

where R_s is the surface resistance of the active element and it depends on the element type and level of excitation. The quantity

$\left|V_1^+ + V_2^+\right|$ has a week dependence on the number of elements *n*. it has a peak value of 2.6 at *n*=3, and approaches 2.0 as $n \to \infty$.

For a given value, for the number of elements, *n* one can determine the proper reference planes from (8), the angle ζ_1 from (9), and the angle $\Delta\psi$ from (10). To determine the best choice of the three-port network parameters we examine the normalized peak electric field $E_n = E_{\max} / \left(\frac{P_{in} Z_3}{A_3 G_3}\right)^{1/2}$, using (11), and the normalized losses $P_{ln} = P_l / \left(\frac{R_s}{Z_3}\left|V_1^+ + V_2^+\right|^2\right)$, using (12).

DESIGN EXAMPLE OF AN OPTICALLY CONTROLLED X- BAND SWITCH

One of the applications of this switch is the high power pulse compression system of the Next Linear Collider [1]. This system operates at 11.424GHz. We can construct the phase shifter and, hence the switch from a series of *four* three-port networks. The three-port network may be composed of a WR90 rectangular waveguide with a circular waveguide coupled to it from the broad side. A propagation of 200 MW in waveguide junctions having similar dimensions has been demonstrated [5]. If the switch is to operate at a 100 MW level, the phase shifter need to handle only 50 MW.

The third arm, in this case, is composed of a circular waveguide carrying the fundamental mode TE_{11}. If the diameter of this waveguide is 2.54 cm, the peak field for a 50MW power level is 140 kV/cm. If the active element in these guides is a silicon wafer, which can be switched optically using a short pulse laser [2], the peak field need to be less than a 100 kV/cm at the wafer. Hence the normalized peak field need to be less than 0.714. If we assume ϕ to be 0; at $6 = 0.881$ the normalized peak field is 0.6, and the normalized losses is 0.914. Hence the peak electric field is 84 kV/cm. When the switch is *on* we assume a carrier density of about $10^{19}/cm^3$ which corresponds to a conductivity of 3.3×10^2. Hence, the losses is 0.46% per element, i.e., a total of 230 kW is being wasted at the silicon wafer. The realizability of the cooling system to take out this power depends on the average power and the pulse length of the rf signal.

CONCLUSION

We presented an abstract analysis and design methodology for a DTSP switch based on several distributed elements. We showed that such a switch, in principle, could be designed to handle a 100 MW at X-band.

REFERENCES

[1] R. D. Ruth et. al., "The Next Linear Collider Test Accelerator," Proc. of the IEEE Particle Accelerator Conference, Washington DC, May 1993, pp. 543-545.

[2] Sami G. Tantawi et. al. “Active High-Power RF Pulse Compression Using Optically Switched Resonant Delay Lines,” IEEE Trans. Microwave Theory Tech., vol. MTT 45, No. 8, August 1997.

[3]A. L. Vikharev, et. al., “Distributed Switches of wave beams and compressors of microwave pulses,” letters to JTF (Russia), Vol. 22, N0. 19, 1996.

[4]R. E. Collin, “Foundations for Microwave Engineering,” Second Edition, McGrow-Hill, Inc. 1992, Chapter 4, pp. 259-260.

[5] Sami G. Tantawi et. al. “The Next Linear Collider Test Accelerator’s RF pulse Compression and Transmission Systems,” Advanced Accelerator Concepts workshop, Lake Tahoe, California, October 12-18, 1996, AIP proceedings 398, pp 805-812.