Criteria for Wide-Band Radial Switch Design

Qingyuan Wang, Michel Lecours, *Fellow, IEEE*, and Claude Vergnolle

***Abstract*—This paper presents criteria for the design of radial switches, such as can be used in electronically steered circular array antennas for satellite communications mobile terminals. The choice of the switching circuit and diode used in each channel is discussed and the required inductance for the diode shunt capacitance compensation for lower insertion loss is given. Analytical formulas are derived for the general case of an ideal transmission-line switch to show the dependence of the return-loss bandwidth on the choices of the line impedance. Important optimization criteria for lower insertion loss and increased bandwidth are drawn. The criteria have been used to guide the design of economical L-band microstrip switches for use in INMARSAT/MSAT antenna arrays, using low-cost printed-circuits and surface-mount plastic-encapsulated p-i-n diodes. Implementation results for insertion loss, reflection coefficient, and isolation between channels are reported.**

***Index Terms*—Microstrip array, microstrip switch, wide-band microwave switch.**

I. Introduction

THE advantages of an electronically steered over a mechanically steered antenna include robustness, faster scanning, acquisition, and tracking, but cost considerations are of paramount importance. Such an electronically steered microstrip antenna array for INMARSAT/MSAT satellite communications mobile terminals is under design in our laboratory. The function of the switch is to open certain channels whose antennas are oriented closest to the direction of the satellite. In order for the antenna array to function well in the operation bands from 1.525 to 1.559 GHz and from 1.627 to 1.661 GHz, with a relative bandwidth of 8.5% from the lower to the upper end of the band, the bandwidth of all components, switch, phase shifters, and patch antennas must be optimized.

A first radial microstrip switch design with an insertion loss of 1.5 dB and reflection coefficient of -10 dB in the 1.545–1.661-GHz band has been reported in [1] and [2] for such an application. A recent paper dealing with this subject can be found in [3]. The motivation of this paper is to explore the possibility of a microstrip switch with substantially lower insertion loss and reflection, by carefully designing the unit switching circuit for each channel.

This paper is comprised of five sections. In Section II, the choice of a simple unit switching circuit with one diode for the switch and with inductance compensation for the diode shunt capacitance is discussed. In order to increase the bandwidth, in Section III, the Q factor of an ideal transmission-line switch is derived, from which the design criteria for a wide-band and low-loss switch are established. In Section IV, the design of an L-band sample microstrip switch using the above criteria is discussed. The simulated and measured results are also presented and compared. In Section V, some conclusions are drawn.

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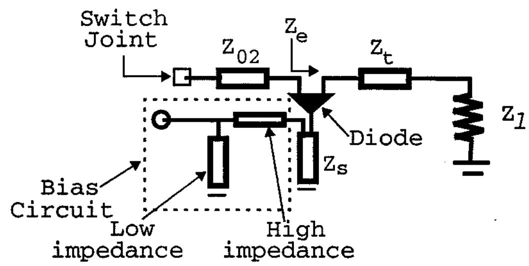

Fig. 1. Unit switching circuit used in the switch.

II. Selection of the Unit Switching Circuit and of the p-i-n Diode for Each Channel

The switch under consideration is composed of m channels with a unit switching circuit in each channel. All channels join together at the switch junction and are fed by a common perpendicular coaxial line of assumed impedance Z_0. The switching circuit can open a channel, allowing the signal to propagate through it, or close it, causing the signal to be reflected. For lower insertion loss and lower cost, a simple switching circuit is preferred. The application of lumped components such as capacitors and resistors should be avoided and the total length of the microwave channel should also be as short as possible to reduce ohmic losses.

Fig. 1 shows the basic unit switching circuit proposed for the design. This switching circuit is composed of a quarter-wavelength transformer of impedance Z_{02}, of another quarter-wavelength transformer of impedance Z_t, and is terminated by a load Z_l. A quarter-wavelength open stub of impedance Z_s is connected in parallel with each channel through a diode. The open stub provides a virtual ground for microwave signals at the cathode of the diode. The effect of the bias circuit defined by the dotted square in Fig. 1 is neglected. For generality, in this and in the following two sections, ideal transmission lines will be used instead of practical transmission lines such as waveguides or microstrips.

A dual-anode diode is used to close each channel or to open it by forward or reverse biasing. Fig. 2 gives the equivalent circuit of such a diode. The inductance L in the figure is the inductance

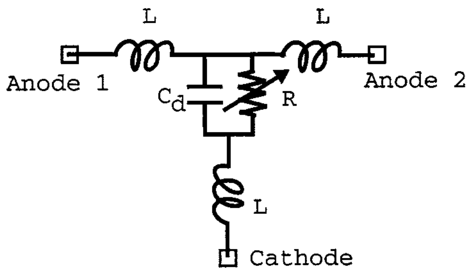

Fig. 2. Equivalent circuit of a p-i-n diode.

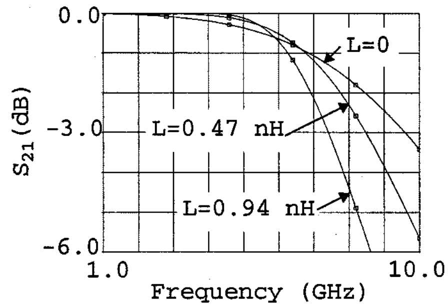

Fig. 3. Insertion loss caused by a reverse biased diode, with its anode lead inductance as the parameter.

of each lead of the diode. The variable resistor R has a small forward residue resistance r_d when the diode is forward biased and the channel is closed. The effect of the shunt capacitance C_d is negligible in this case. When the diode is reverse biased, the variable resistor R is very high (it is assumed to be 10 000 Ω in our design) and the shunt capacitance becomes important. The channel is open with some reflection and insertion loss caused by the shunt capacitor.

A good diode for such an application would have a very small forward residue resistance r_d and a very small shunt capacitance C_d. However, this is not the case for commercially available diodes. Diodes with small forward residue resistance r_d usually have a high shunt capacitance C_d or vice versa. A higher residue resistance will cause power leaking through the closed channels, resulting in poor isolation. A higher shunt capacitance, on the other hand, will cause reflection in an open channel, resulting in higher insertion loss. A compromise was achieved by using a diode with a small residue resistance and by using a compensation inductance for the high shunt capacitance.

To compensate for the shunt capacitance, a so-called constant-k low-pass filter should be formed, which requires the anode lead inductance to be [4]

$$L = \frac{Z^2}{2} C_d \tag{1}$$

where Z is the impedance of the transmission lines connected to both anodes of the diode. The effect of the cathode lead is neglected considering that it can be compensated by adjusting the length of the open stub connected to it.

For a p-i-n diode with $r_d = 0.6\ \Omega$, $C_d = 0.75$ pF, Fig. 3 shows the resulting insertion loss versus frequency for different choices of lead inductance. The transmission-line impedance is assumed to be $Z = 50\ \Omega$. When $L = 0$ nH, in the band from 1.525 to 1.661 GHz, the shunt capacitance will cause in each open channel an insertion loss of at least 0.16 dB and a reflection of at least -14.35 dB. Whereas when $L = 0.94$ nH is chosen, the insertion loss is lower than 1.43×10^{-4} dB, and the reflection is lower than -42.50 dB over the whole band. When the diode is used at higher frequencies, the improvement in increasing the anode lead inductance will be more apparent. The improvement is also more important in the case of a higher diode shunt capacitance. In the case of $C_d = 2.2$ pF [1], [2], and with $Z = 50\ \Omega$, when $L = 0$ nH, the insertion loss will be as high as 1.25 dB and the reflection -6.08 dB. If the compensation inductors are chosen according to (1), with $L = 2.75$ nH, the insertion loss will be lower than 0.18 dB and the reflection -14.66 dB.

III. Bandwidth and Insertion Loss of an Ideal Transmission-Line Switch

Let us now consider a radial switch having a total of m channels, among which n channels are open and the other $m - n$ channels are closed. Each channel has the configuration shown in Fig. 1 and an ideal transmission-line model for each microwave channel is again used here for generality.

The transfer matrix of a quarter-wavelength transmission line of center frequency f_0 and arbitrary impedance Z_{00} at a normalized frequency difference $x = \pi \Delta f / f_0$ is

$$\begin{bmatrix} -\frac{1}{2}x & jZ_{00} \\ jY_{00} & -\frac{1}{2}x \end{bmatrix}. \tag{2}$$

Using such a matrix for each of the transmission lines, the input admittance for n open channels in parallel can be calculated to be

$$Y_{\text{open}} = \frac{1}{Z_0} + j\frac{x}{2Z_0} \frac{\left(\sqrt{\overline{Z_l}} + \sqrt{n}\right)\left(\sqrt{n\overline{Z_l}} - \overline{Z_e}\right)}{\sqrt{n\overline{Z_l}\,\overline{Z_e}}}. \tag{3}$$

Here, $Z_e = Z_t^2 / Z_l$, as defined in Fig. 1, is the equivalent load impedance seen at the diode. The impedances with over bars are normalized with respect to the feed-line impedance Z_0. In order to match the switch to the feed line, we have

$$Z_{02} = \sqrt{nZ_0 Z_e}. \tag{4}$$

In the same way, for the $m - n$ closed channels, we have

$$\begin{aligned} Y_{\text{close}} = &\frac{(m-n)\overline{r_d}}{nZ_0\left(\overline{r_d} + \overline{Z_e}\right)} \\ &+ j\frac{x}{2Z_0}\left[\frac{(m-n)\left(\overline{Z_s} + \sqrt{n\overline{Z_e}}\right)}{n\overline{Z_e}}\right. \\ &\left. - \frac{(m-n)\overline{r_d}^2\sqrt{\overline{Z_e}}}{n^{3/2}\left(\overline{r_d} + \overline{Z_e}\right)^2}\right]. \end{aligned} \tag{5}$$

The total admittance of the switch from the feed point is

$$Y_{\text{in}} = Y_{\text{open}} + Y_{\text{close}}. \tag{6}$$

For a parallel *LRC* circuit, when the frequency is close to its oscillating frequency $f_0 = 1/2\pi\sqrt{LC}$, the input admittance can be written as

$$Y_{\text{in}} = \frac{1}{R} + j4f_0Cx \tag{7}$$

and its Q factor is

$$Q = 2\pi f_0 RC. \tag{8}$$

In the same way, from (6), the Q factor of the switch is

$$Q = \frac{\pi}{4}\frac{1}{1+\dfrac{(m-n)\overline{r_d}}{n\left(\overline{r_d}+\overline{Z_e}\right)}} \cdot \left(\frac{\left(\sqrt{\overline{Z_l}}+\sqrt{n}\right)\left[\sqrt{n\overline{Z_l}}-\overline{Z_e}\right]}{\sqrt{n\overline{Z_l}}\,\overline{Z_e}} + \frac{(m-n)\left[\overline{Z_s}+\sqrt{n\overline{Z_e}}\right]}{\overline{Z_e}} - \frac{(m-n)\overline{r_d}^2\sqrt{\overline{Z_e}}}{n^{3/2}\left(\overline{r_d}+\overline{Z_e}\right)^2}\right). \tag{9}$$

If the switch is matched at its center frequency, the relative bandwidth for a voltage standing-wave ratio (VSWR) lower than S is

$$\text{BW} = \frac{1}{Q}\frac{S-1}{\sqrt{S}}. \tag{10}$$

Broad bandwidth is achieved when the Q factor in (9) is small. Accordingly, we can establish the following criteria for wide-band switch design.

1) **Large n or small $m - n$ when m is fixed**. This is easy to understand because both cases are tending toward matching a transmission line with n parallel transmission lines with quarter-wavelength transformers.
2) **Low impedance of the open stubs Z_s**. In (9), we recognize that the contribution of the $m-n$ closed channels to the Q factor is represented by the second term in the large bracket. Lowering Z_s, the Q factor will be decreased.
3) **High equivalent load impedance Z_e**. In the same large bracket in (9), both the second and first terms, which represent the contribution of the n open channels to the Q factor, will decrease with increased Z_e, resulting in a wider bandwidth. The third term in the bracket, the contribution of the residue resistances of the diodes when they are forward biased, is usually very small compared to the other two terms.

For each open channel, at the center frequency of the switch, the residue resistance of each forward-biased diode in parallel with Z_e provides a shunt impedance of $Z_{02}^2(r_d+Z_e)/(r_dZ_e)$ at the feed port of the switch. The total $m-n$ open channels provide a shunt resistance of $Z_{02}^2(r_d+Z_e)/(r_dZ_e(m-n))$ to the n channels, which are matched to the feed line. The insertion loss due to the $m-n$ deactivated channels at the center frequency is

$$T(\text{dB}) = 20\log\left(1-\frac{(m-n)\overline{r_d}}{2n(\overline{r_d}+\overline{Z_e})}\right). \tag{11}$$

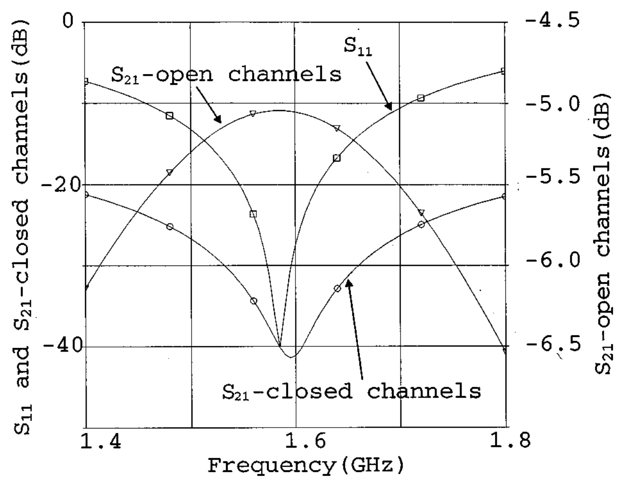

Fig. 4. Simulated return loss, insertion loss, and isolation of a switch with an effective load impedance of 50 Ω.

According to (11), for the insertion loss, we can draw the following criteria.

1) When n (the number of activated channels) is fixed, the insertion loss will increase with $m - n$, the number of deactivated channels.
2) When $m - n$ (the number of deactivated channels) is fixed, the insertion loss will decrease with n, the number of activated channels.
3) The insertion loss can be decreased by increasing the equivalent load impedance Z_e at the p-i-n diodes.

IV. Microstrip Switch Design Under the Guidance of the Design Criteria

The above design criteria were used to guide the design of microstrip switches. The p-i-n diodes used have a shunt capacitance of 0.75 pF and a residue resistance of $r_d = 0.6\ \Omega$. The inductances of each of the two anode leads and of the cathode lead were measured to be 0.47 nH. In Section II, according to the unit switching circuit shown in Fig. 1, it was calculated that the total inductance of the anode leads should be 0.94 nH. The extra 0.47 nH plus the microstrip transformer of impedance Z_{02}, on the left-hand side of the diode, behaves as the same microstrip line with reduced length. The extra 0.47-nH inductance on the right-hand side of the diode was provided by a microstrip of narrower width. As pointed out in Section II, the inductance of the cathode lead was compensated by a quarter-wavelength open stub with reduced length.

Fig. 4 shows the simulated return loss, insertion loss, and isolation of a microstrip switch with parameters $Z_s = 43.8\ \Omega$, $Z_e = 50\ \Omega$, $Z_{02} = 86.7\ \Omega$. The isolation is the power attenuation from the feed of the switch to a closed channel. The overall insertion loss was obtained by subtracting 4.771 dB from the insertion loss obtained from the figure because three channels were open. From Fig. 4, we can see that in the whole operation band, the return loss was lower than −14.48 dB, the insertion loss lower than 0.45 dB, and the isolation better than 28.76 dB.

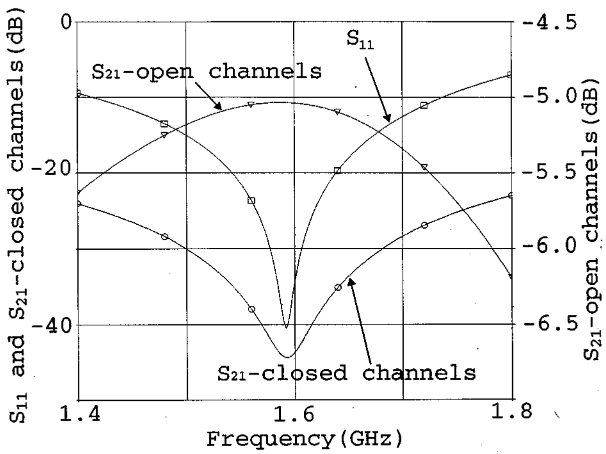

Fig. 5. Simulated return loss, insertion loss, and isolation of a switch with an effective load impedance of 70 Ω.

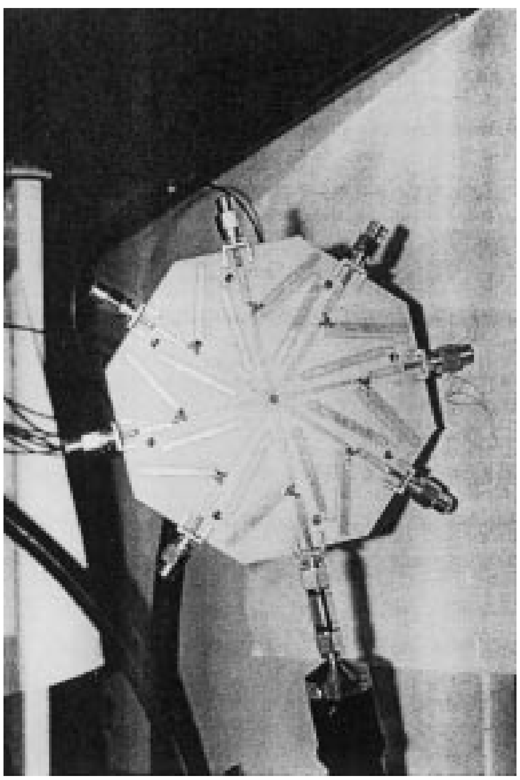

Fig. 6. L-band microstrip switch with an effective load impedance of 50 Ω under test.

In Section III, it was mentioned that both bandwidth and insertion loss will decrease with the effective load impedance Z_e. This has been verified by the simulation of a second switch. Compared with the first one, Z_e was increased from 50 to 70 Ω, and from the matching condition of (4), Z_{02} was increased from 86.7 to 102.47 Ω. The simulated results are shown in Fig. 5. The return loss was lower than −16.41 dB, the insertion loss lower than 0.39 dB, and the isolation better than 32.07 dB.

The first switch, whose simulation results were given in Fig. 4, was implemented and Fig. 6 shows the circuit fabricated on an economical substrate, with one channel connected to Port 2 of an HP 8703 Light-Wave Component Analyzer and the other seven channels terminated by 50-Ω matched loads. Fig. 7 shows the return loss, insertion loss, and isolation measured by the analyzer. From Fig. 7, for the whole band from 1.525 to 1.661 GHz, the insertion loss was lower than 0.50 dB, the reflection lower than −13.76 dB, and the isolation better than 28.45 dB. Compared with the simulations, all results agree with each other very well. The switch was also found to be very symmetrical and the measurements at each of the three open channels gave essentially the same results.

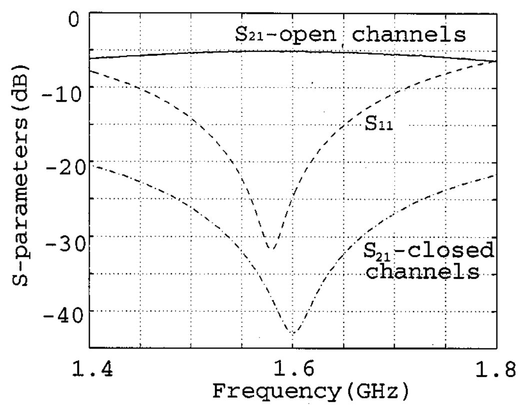

Fig. 7. Measured return loss, insertion loss, and isolation of a switch with an effective load impedance of 50 Ω corresponding to the simulated results of Fig. 4.

V. Conclusions

This paper has presented design criteria of a wide-band radial switch such as can be used in antenna arrays for satellite communications mobile terminals. Extra anode lead inductance has been suggested to compensate for the shunt capacitance of the diode, which will otherwise cause a high insertion loss and a high return loss in an open channel. In order to show the factors limiting the bandwidth, the Q factor of a radial switch composed of ideal transmission lines was derived and used to establish criteria for wide bandwidth switch design. According to the formula, the number of closed channels should be small and the number of open channels large to give a wide bandwidth. When these numbers are specified, lowering the impedance of the open stubs and increasing the equivalent load impedance seen at each diode will also increase the bandwidth.

The design criteria were verified by simulations and were used to guide the implementation of microstrip switches. In the low-cost test switch presented in this paper, the measured insertion loss was lower than 0.50 dB, reflection lower than −13.76 dB, and the isolation better than 28.45 dB, for the whole band from 1.525 to 1.661 GHz.

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