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Design Methodology of Loaded-Line Phase Shifters based on Silicon and Gallium Arsenide Bulk P-I-N Diodes

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Abstract. A design methodology of loaded-line phase shifters based on bulk p-i-n diodes is presented. The design methodology is verified with phase shifters based on Silicon (Si) and Gallium Arsenide (GaAs) p-i-n diodes with different geometry. The responses of circuit design of 45° phase shift are analyzed. The circuits designed with bulk p-i-n diodes I-layer thickness of 50 microns reaches a variation of 4.8 degrees in phase shift responses in a bandwidth of 1GHz, at the center frequency of 10GHz. The reflection coefficient responses are less than 0.1 for the forward and reverse biased p-i-n diode.

Keywords: Loaded-Line Phase Shifters, bulk p-i-n diodes, Silicon and Gallium Arsenide.

1 Introduction

Phase shifter circuits are essential for radars and actually for phased array antennas in wireless communication systems. In the last application, phase shifter circuits provide phase increments to each antenna element of the array in order to redirect the beam to different directions. In transceiver equipments, phase shifter circuits can be digital and programmable to control the phase in adaptive manner to the channel conditions [1, 2].

Digital phase shifter circuits can have various topologies, but in general the signal is directed at two different technologies. The first technology works with a fixed phase difference and the second one controls the phase change of a network by switching circuits inside or outside. There are six types of digital controlled phase shifters, each of them with its own limitations: online connections (for narrow band), reflection (poor coupling), loaded line connection (suitable only for small bits), switching from low pass to high pass (high inserted loss), switched network (suitable only for bits of 180°), and FET integrated circuits (suitable for bits of small phase) [2].

The best options for the design of constant phase circuits are switching networks and loaded line techniques [3, 4]. These linear phase designs are extensively used in phased array antennas with true-time delay (TDD) [3].

Although there are a variety of phase shifter circuits, loaded-line circuits offer simplicity, low insertion loss and good performance for small phase changes [4]. Likewise, load line phase shifters are characterized by their simplicity manufacturing and to achieve low insertion loss, especially for phase shifts less than 90 degrees [5]. Due to mismatches occur with a circuit of 90° phase shift, the application of loaded-line phase shifters is limited to small phase shifts.

2 P-I-N Diodes

The p-i-n diodes are still the preferred option for the design of loaded-line phase shifters. The p-i-n diodes are in high demand, mainly by cost factor, for mobile phones of single and double sideband. They used a special circuital configuration that allows forward polarized p-i-n diodes for transmission, which is not possible in designs of three and four bands. For these cases the best option is PHEMT switches Gallium Arsenide (GaAs) [6].

For many years, silicon p-i-n diodes have been widely used in loaded-line phase shifters for microwave to control microwave signals, especially in switches, phase shifters and variable attenuators circuits that operate with high power signals and from RF to millimeter frequencies [7].

There are proposals to use other semiconductor materials for the design of p-i-n diodes, in order to optimize the performance of switches and phase shifter circuits. There are two factors that researchers wish to improve, insertion loss and switching speed. A low insertion loss prevents degradation of the signal to noise ratio at the receiver of a communication system [8]. The switching speed of the p-i-n diode depends on the time required to inject or remove the charge of the intrinsic region of the diode. The rapid evacuation of the carriers from the intrinsic region, after the state of low impedance of the diode, limits the switching speed too. This speed depends on the carrier mobility and the thickness of I layer needed to support a bias voltage breakdown. Due to the ambipolar mobility of the semiconductor, silicon p-i-n diodes reach a few nanoseconds in switching speed.

A proposal is GaAs p-i-n diodes. These require low value of reverse voltage to achieve a very low junction capacitance in reverse bias situation. GaAs has a direct recombination of minority carriers, which limits the lifetime of carriers within 10 nanoseconds. Similarly, this results in a rapid evacuation of the charge of the intrinsic region.

3 P-I-N Diode Equivalent Circuit

The equivalent circuit model of a p-i-n diode type "bulk" operating with microwave frequency signals consists of an inductor L_d in series with a R_s resistance in forward bias state. Under conditions of reverse bias, the model consists of the same inductance L_d in series with a C_j capacitance.

Figure 1 shows the "bulk" p-i-n diode equivalent circuit in forward (P.D.) and reverse (P.I.) bias states.

4 Junction Capacitance and Series Resistance of P-I-N Diodes

The same procedure was followed in [9] to calculate the parameters: junction capacitance C_j $[pF]$ and R_s $[\Omega]$ series resistance of the Si and GaAs "bulk" p-i-n diodes used for the design of loaded-line phase shifters.

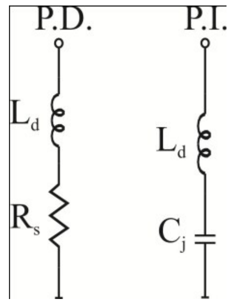

Fig. 1. "Bulk" p-i-n diode equivalent circuit.

To estimate de junction capacitance the following equation was used [10]:

$$C_j \approx \frac{\varepsilon_0 \varepsilon_R \pi A^2}{4W}, \quad (1)$$

where A $[cm]$ is the union diameter, W $[cm]$ is the I layer p-i-n diode thickness, ε_R is the relative permittivity of the semiconductor material and ε_0 is the free space permeability $\left(8{,}85 \times 10^{-14} \frac{F}{cm}\right)$.

The junction capacitance C_j is directly proportional to the p-i-n diode diameter and inversely proportional to the intrinsic region thickness W of the p-i-n diode. A p-i-n diode with low junction capacitance C_j has good responses to interferences, while its thickness $W_{\mu m}$ is high [9].

Series resistance R_s of the p-i-n diodes used was found using the equation:

$$R_T(f) = R_I + 2R_j(f)\ , \quad (2)$$

where R_I is the intrinsic región resistance and $R_j(f)$ is the union resistance that conform de p-i-n diode [11]. Equation (2) allows to find the total p-i-n diode resistance under forward bias state for a given signal frequency (f $[GHz]$), and is function of the intrinsic region thickness, the ambipolar diffusion length L, the carrier life time (τ) and the direct bias current (Io).

5 P-I-N Diodes considered in the Design of the Phase Shifter Circuits

5.1 Silicon P-I-N Diodes

Table 1 shows the values of union capacitance (C_j) and series resistance (R_s) obtained with physical parameters of "bulk" Silicon (Si) p-i-n diodes considered for the design of phase shifter circuits. A forward bias current of 30 mA was considered at 10 GHz of operation frequency. The selection of the "bulk" type p-i-n diodes was according to their characteristic of carrier life time in the intrinsic region, whose value is between 300 nanoseconds and 3 microseconds [8].

Table 1. Physical parameters of silicon "bulk" type p-i-n diodes.

Diode	A(μm)	W(μm)	L(μm)	$\tau(\mu s)$	$C_j(pF)$	$R_s(\Omega)$
D1	178	25.4	31	0.5	0.102	0.27
D2	254	50.8	44	1.0	0.104	0.52
D3	660	50.8	62	2.0	0.705	0.27

5.2 Gallium Arsenide P-I-N Diodes

Table 2 shows the physical parameters of GaAs p-i-n diode considered for the design of the phase shifter circuit, according to the proposed in [12].

Table 2. Gallium Arsenide "bulk" type p-i-n diode parameters [12].

Parameter	Value
Typical direct bias current, I_0 (mA)	30
Acceptor impurity concentration, N_A (cm^{-3})	2×10^{19}
Donor impurity concentration, N_D (cm^{-3})	1×10^{15}
Diode diameter, D (μm)	50
Inverse bias voltage, V_r (V)	5.0
Carrier lifetime in the I region, τ (ns)	1.0

The junction capacitance and total series resistance that characterize the GaAs "bulk" type p-i-n diode at 10 GHz of frequency were found using the same procedure described in [9].

GaAs p-i-n diode: $C_j = 68.7\ fF, R_t = 1.33\ \Omega$. Considered as diode 4 (D4).

6 Loaded-Line Phase Shifter Equivalent Circuits

The objective of the phase shifter circuit design is that the phase shift (ϕ), added to the radio frequency signal, be constant as possible in a wide bandwidth. Also, the loaded-line circuit must introduce minimum insertion loss with low reflection coefficient.

7 Loaded-Line Phase Shifter Operation

The phase shifter circuit is installed in the transmission line whose characteristic impedance is Z_0 $(= 1/Y_0)$, as shown in figure 2. The circuit consists of two admittances ($Y_i = G_i + jB_i$) separated by a transmission line of approximately one quarter of wavelength $(\theta \cong 90°)$, whose characteristic impedance is Z_T. The subscript i refers to the state of the diodes: forward ($i = 1$) or reverse ($i = 2$) according to the signal emitted by its control circuits. Diodes are considered to have negligible losses, i.e. $G_i = 0$.

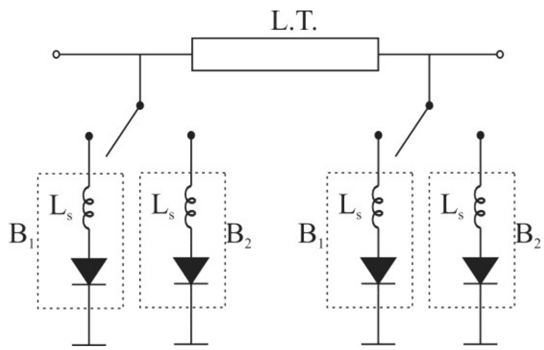

Fig. 2. Loaded-Line Phase Shifter.

Each admittance is composed of an inductor with $L_s(nH)$ in series with the p-i-n diode. This inductance can be used to tune and improve the responses of the circuit. P-i-n diodes switch between forward (on) and reverse (off) states according to the bias current received by its control circuits.

Figure 3 shows the equivalent circuits of the phase shifters with "bulk" type p-i-n diodes for forward and reverse bias states.

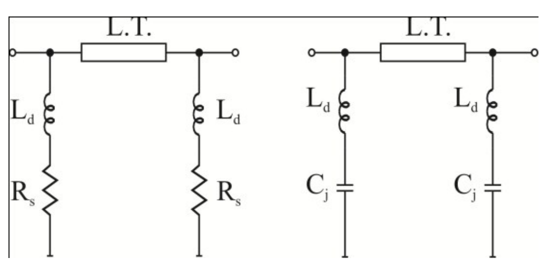

Fig. 3. Equivalent circuits of the phase shifters with "bulk" type p-i-n diodes.

The equivalent susceptances at forward and reverse bias states are:

$$B_{on} = -\frac{1}{R_s + wL}, \quad (3)$$

$$B_{off} = \frac{w\,C_j}{1 - w^2 L C_j}, \quad (4)$$

where $L = L_s + L_d$, and $w = 2\pi f$, and $f\,(GHz)$ is the operation frequency of the phase shifter.

Design Methodology

In order to achieve the loaded-line phase shifter circuit design the impedance of the transmission line $Z_T\ (= {Y_T}^{-1})$ must be found based on the equivalent circuit parameters of the diodes.

Bahl and Gupta in [13] provides the equations of the susceptances B_{on}, B_{off} and the Y_T admittance for the design of the phase shifter circuit with mínimum insertion loss, a voltage standing wave ratio equal to unity and a phase shift constant as possible on a wide bandwidth.

The line transmission admittance is: $Y_T = Y_0 \sec(\phi/2) \sin\theta$ and the equivalent susceptance in forward and reverse bias states are:

$$B_{off} = Y_0[\sec(\phi/2)\cos\theta + \tan(\phi/2)],$$

$$B_{on} = Y_0[\sec(\phi/2)\cos\theta - \tan(\phi/2)].$$

If the phase shifter circuit uses "bulk" type p-i-n diode, the inductance $L(nH)$ is obtained by equating (4) with the corresponding equation B_{off} of the phase shifter, resulting in:

$$L = \frac{1}{w^2 C_j} - \frac{\sin(\theta)}{w Y_T [\cos\theta + \sin(\phi/2)]} \quad (5)$$

Likewise, by equating (3) with the corresponding susceptance B_{on} together with (5) gives the expression for the impedance of the transmission line Z_T.

$$Z_T = \frac{-[\cos^2\theta - \sin^2(\phi/2)](1 + wC_j R_s)}{2w\,C_j[\sin\theta\,\sin(\phi/2)]} \quad (6)$$

With equation (6) and the equation required for the admittance of the transmission line phase shifter Y_T, we obtain the equation of the characteristic admittance Y_0:

$$Y_0 = \frac{-w\,C_j \sin\phi}{(1 + w\,C_j\,R_s)[\cos^2\theta - \sin^2(\phi/2)]} \quad (7)$$

Equation (7) is a direct function of the union capacitance p-i-n diodes C_j and the transmission line (L.T.) phase shifter. The diode series resistance R_s has no significant effect on the admittance Y_0. For a phase shift of 45°, we obtain the surface that relates the characteristic impedance Z_0 with the length of the transmission line (θ) for the property C_j. Figure 4 shows this dependence.

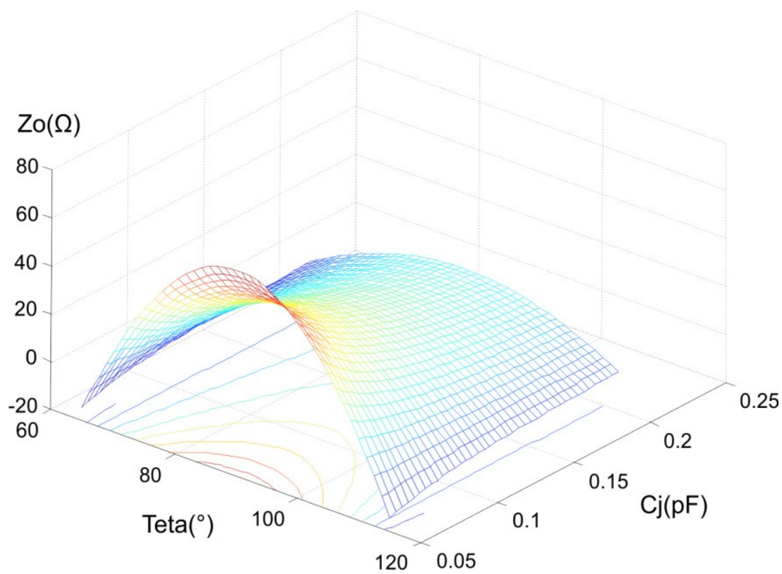

Fig. 4. Impedance Z0 versus C_j transmission line length θ.

It can be seen that the GaAs p-i-n diode has a higher degree of adaptation of the phase shifter circuit to the line impedance Z0 due to its characteristic of low junction capacitance in the order of tens of fem to farads (fF). Circuits with p-i-n diodes D1 and D2 can be used in line impedance Z0 with low value for high capacitance characteristics C_j. The diode D3 has poor adaptive response to high Z0 impedance lines, due to their higher capacitance value C_j.

Analysis of Design Results

Below are the results of design of circuits designed to phase shift of 45° with the methodology presented in the previous section and using p-i-n diodes type "bulk" D1 to D4.

We analyzed the responses of phase shift at 1 GHz of bandwidth at the center frequency of 10 GHz. Calculated design parameters are shown in Table 3.

The inductance $L_{d,nH}$ is characteristic of p-i-n diode, and is chosen a value $L_{d,nH}$ less than the inductance L_{nH}. An inductor of inductance $L_{s,nH}$ will be installed in series with the diodes in the phase shifter circuit.

Table 3. Results of Loaded-line Phase Shifters design.

Diode	$\theta(°)$	$z_t(\Omega)$	$z_0(\Omega)$	$L_{nH} = (L_{s,nH} + L_{d,nH})$
D1	90	29.91	32.37	1.2395
D2	90	29.38	31.69	1.2137
D3	90	4.37	4.69	0.1775
D4	90	44.59	47.98	1.8326

The equivalent circuits from Figure 3 were simulated using license-free software. Figure 5 shows the results of phase shift and reflection coefficients in situations of forward and reverse bias for a linear phase response in 1GHz of bandwidth.

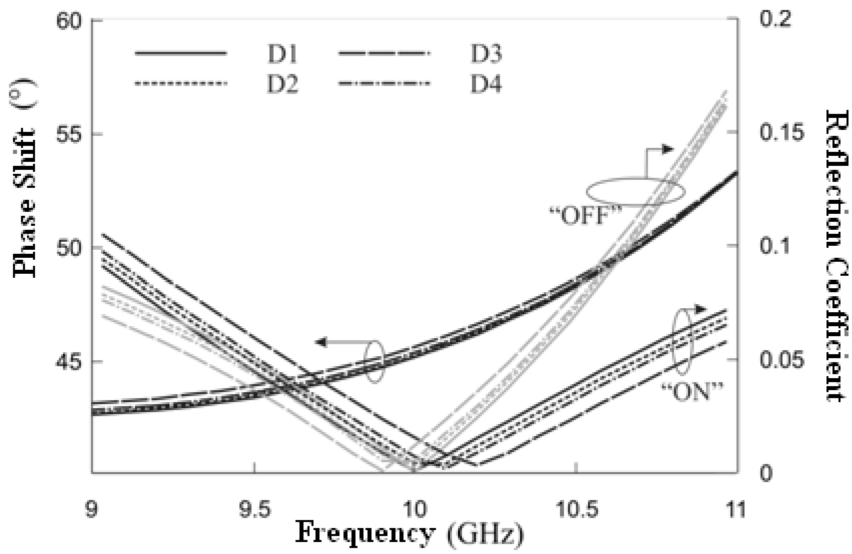

Fig. 5. Phase shift and reflection coefficient responses in situations of forward and reverse bias states.

It can be seen that the phase shift responses using p-i-n diodes type "bulk" vary 4.8 degrees in a bandwidth of 1 GHz, and their responses reflection coefficient is less than 0.1.

The series resistance (R_s) of the p-i-n diodes type "bulk" is a parameter which depends on the response of the phase shifter insertion loss in a particular linear bandwidth.

Conclusions

A methodology for the design of loaded-line phase shifters based on "bulk" type p-i-n diodes was presented. The Methodology was verified with the design of 45 ° phase shifter circuit with silicon and gallium arsenide p-i-n diodes. GaAs p-i-n diodes allow greater degree of adaptation to transmission line of impedance Z0 due to its characteristic of low junction capacitance. The responses of the 45 ° phase shifter with "bulk" type p-i-n diodes of 50 micron intrinsic layer exhibit reflection coefficients less than 0.1 with a variation of 4.8° phase shift on 1 GHz of bandwidth at the center frequency 10 GHz.

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