2.45 GHz T/R, RF switch for e.g. bluetooth application using PIN diodes

1 Introduction.

One of the most important building blocks for today's wireless communication equipment is a high performance RF switch. The switch main function is to switch an RF port (ANT) between the transmitter **(TX)** and the receiver **(RX)**.The most important design requirements are, Low insertion Loss **(IL)**, Low intermodulation distortion,**(IMD)**, High isolation between TX and RX, Fast switching and Low current consumption especially for portable communication equipment. This application note addresses a transmit and receive switch for 2.4-2.5 GHz the unlicensed ISM band, in which e.g. the bluetooth standard operates. The design demonstrates a high performance T-R switch utilising low cost Philips BAP51-02 PIN Diodes as switching elements.

2 PIN diode switch design.

There are a number of PIN diode based, single pole double throw (SPDT) topologies, which are shown in the figures 1,2 and 3. Al these topologies are being used widely in RF and microwave design. They all will give good performance, due to their symmetry they will show the same performance in both the RX and TX mode. The disadvantage of these topologies is the need of a pair of digital control signals, and in both TX and RX mode bias current is needed.

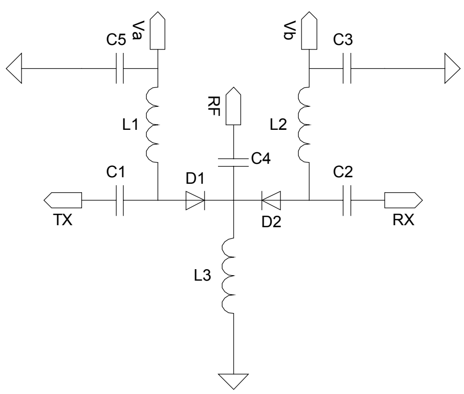

Figure 1. *SPDT switch with series diodes*

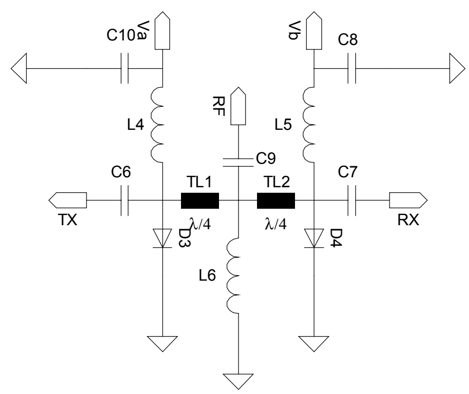

Figure 2. *SPDT switch with λ/4 sections to permit shunt diodes*

The topology we used for the design in this application note is shown in fig 4. Typically this is a combination of figure 1 and 2. The design consists of a series-connected PIN diode, placed between the transmitter-amplifier and antenna, and a shunt-connected PIN diode at the receiver-port, which is a quarter wavelength away from the antenna. In the transmit-mode both diodes are biased with a forward bias current. Both diodes are in the low impedance state. Which means a low-loss TX-ANT path and a protected RX port from the TX power.

The $\lambda/4$ transmission line transforms the low impedance at the RX port to a high impedance at the antenna. In the receive mode both diodes are zero biased (high impedance state), which results in a low loss path between antenna and receiver and high isolation ANT-TX path. One of the advantages of this approach is no current consumption is needed in the receive mode.

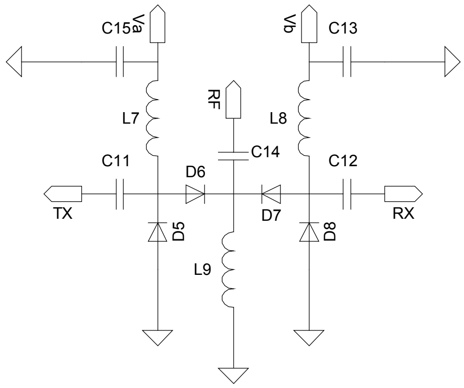

Figure 3. *SPDT switch with series shunt diodes which results in high isolation*

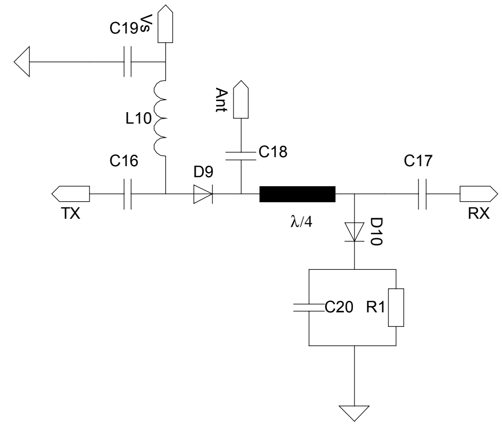

Figure 4. *SPDT switch with a combination of a series and a shunt connected PIN diode.*

The PIN diodes used in an switch like this should have low capacitance at zero bias(V_R=0V), and low series resistance at low forward current. The BAP51-02 typical shows 0.4pF@0V;freq=1MHz and 2 Ω @3mA;freq=100MHz. For the shunt diode also low series inductance is required, for the BAP51-02 this is 0.6 nH.

3 Circuit design.

Circuit and Layout has been designed with the use of Agilent's Advance Design System (ADS). The target performance of the switch is shown in table 1.

Mode	RX (0V)	TX(3mA)
Insertion Loss	< 0.65 dB	< 0.8 dB
Isolation TX/RX	>18 dB	>14.5 dB
Isolation RX/Ant	>16.5	-
Isolation TX/Ant	-	>14.5dB
VSWR RX	<1.2	-
VSWR TX		<1.3
VSWR Ant	<1.2	<1.3
Power handling	+20dBm	+20dBm
Current consumption		3mA @ 3.7V

Table 1

The ADS circuit of the switch is given in figure 5. Notice that D1 is the series connected PIN diode in the receive path en D2 is connected in shunt in the receive RF path. DC bias current is provided through inductance L1, and limited to about 3mA by resistor R1=680 Ω. Notice also that the λ/4 microstripline (width 1.136mm, length =16.57mm) is divided into several sections in order to save some board space. All the footprints for the SMD components have been modelled as a gap and a piece of stripline in order to approach the actual practice of the design on PCB.

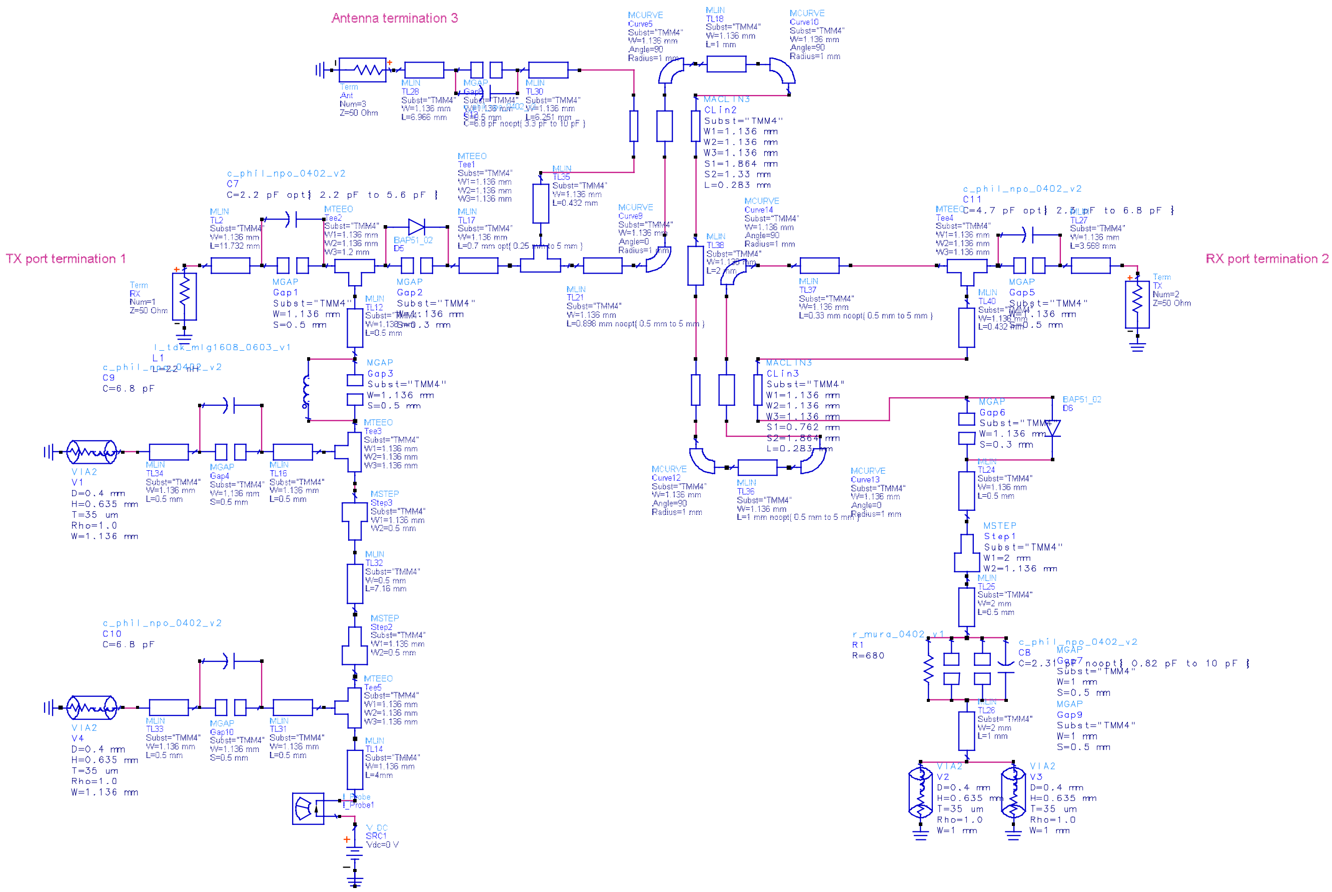

Figure 5 ADS circuit file

The discontinuity effects of the microstrip to coaxial interface have not been taken into account.

4 BAP51-02 model.

The silicon PIN diode of the Philips semiconductors BAP51-02 is designed to operate as a low loss high isolation switching element, and is capable of operating with low intermodulation distortion. The model for the BAP51-02 PIN diode for an ADS environment is shown in figure 6. The model consists of two diodes, in order to achieve a fit on both DC and RF behaviour. Diode1 is used to model the DC voltage-current characteristics, Diode 2 is the PIN diode build in model of ADS and is used to model the RF resistance versus DC current behaviour of the PIN diode-model. Both diodes are connected in series to ensure the same current flow. For RF the PN junction Diode1 is shorted by an ideal capacitor(DC block), while the portion of the RF resistance, which reflects the residual amount of series resistance is modelled with R1=1.128 Ω. To avoid affecting the DC performance this resistor is shunted with the ideal Inductor (DC feed). Capacitance C2 and inductors L2 and L3 reflect the package parasitics. The here described model is a linear model that emulates the DC and RF properties of the PIN diode from 6 MHz up to 6 GHz.

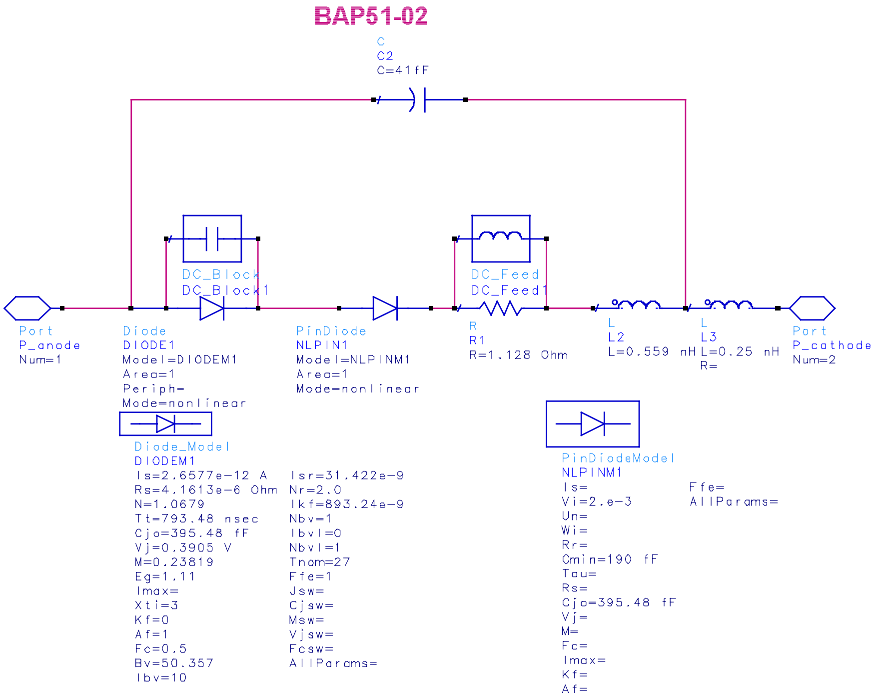

Figure 6; BAP51-02 Small Signal Model for an ADS environment

5 Circuit and Layout Description

The circuit diagram for the switch is shown in figure 7 and the PC board layout is shown in figure 8. The bill of materials for the switch is given in table2.

For the PC board 0.635mm thick FR4 material (ε_r = 4.6)metalized on two sides with 35 µm thick copper, 3 µm gold plated was used. On the test board SMA connectors were used to fed the RF signals to the design.

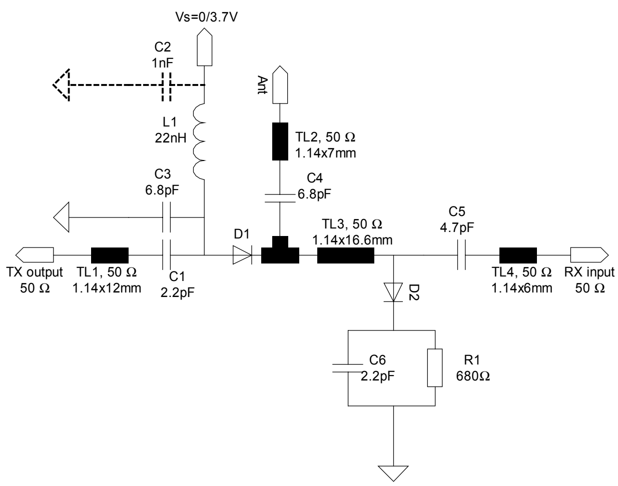

Figure 7; circuit diagram

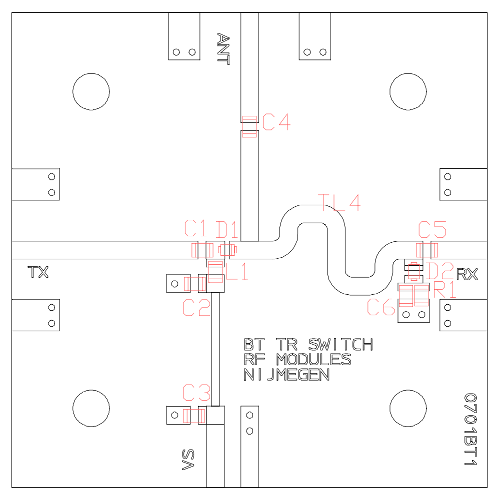

Figure 8; PC board Layout.

Component	Value	Footprint	Manufacturer
C1	2.2 pF	0402	Philips
C2*	1 nF	0402	Philips

C3	6.8 pF	0402	Philips
C4	6.8 pF	0402	Philips
C5	4.7 pF	0402	Philips
C6	2.2 pF	0402	Philips
R1	680 Ω	0402	Philips
D1	BAP51-02	SC79	Philips
D2	BAP51-02	SC79	Philips
L1	22 nH	1005	Taiyo yuden
TL1	λ/4;50 Ω		on the PCB

*Table 2 Bill of materials *C2 is optional.*

6 Measurement results.

In table 3 the measured performance of the switch is summarised. In figure 9, both the simulation and Measurement results in TX mode (3.7V/3mA) is shown, for the RX mode this can be seen in fig.10.

	Mode	
parameter	RX (0V)	TX(3mA)
Insertion Loss @ 2.45GHz	< 0.57 dB	< 1.0 dB
Isolation TX/RX @ 2.45GHz	>20.4 dB	>23.6 dB
Isolation Ant/RX @ 2.45 GHz	-	>23.5 dB
Isolation TX/Ant @2.45 GHz	>19.76 dB	-
VSWR RX @2.45 GHz	1.24	-
VSWR TX @2.45 GHz	-	1.35
VSWR Ant @2.45 GHz	1.19	1.29
IM3 Pin 0 dBm f1=2.449 GHz f2=2.451 GHz	+39 dBm	+40 dBm
IP3 Pin 0 dBm f1=2.449 GHz f2=2.451 GHz	+43.8 dBm	+44.8 dBm
IM3 Pin +20 dBm f1=2.449 GHz f2=2.451 GHz	+38.5 dBm	+39.5 dBm
IP3 Pin +20 dBm f1=2.449 GHz f2=2.451 GHz	+43.3 dBm	+44.3 dBm
Power handling	+20 dBm	+20 dBm
Current consumption		3mA @ 3.7V

Table 3 measured switch performance.

Intermodulation distortion measurements were performed as follows. In both RX and TX state, first the measurements were done with two input-signals, each at 0 dBm and second each signal at +20 dBm. In transmit state these signals were applied to the TX port, distortion was measured at the antenna port, while the RX port was terminated with 50Ω. In receive state the two signals were applied to the ANT port, distortion was measured at the RX port, with the TX port terminated.

According to reference 2, the third order harmonic distortion product is 9.54 dB less than the third order Intermodulation product, the third order harmonic intercept point IP3 is 9.54/2 higher than the third order Intermodulation intercept point IM3.

simulation and measurement results in transmit mode Is=3mA

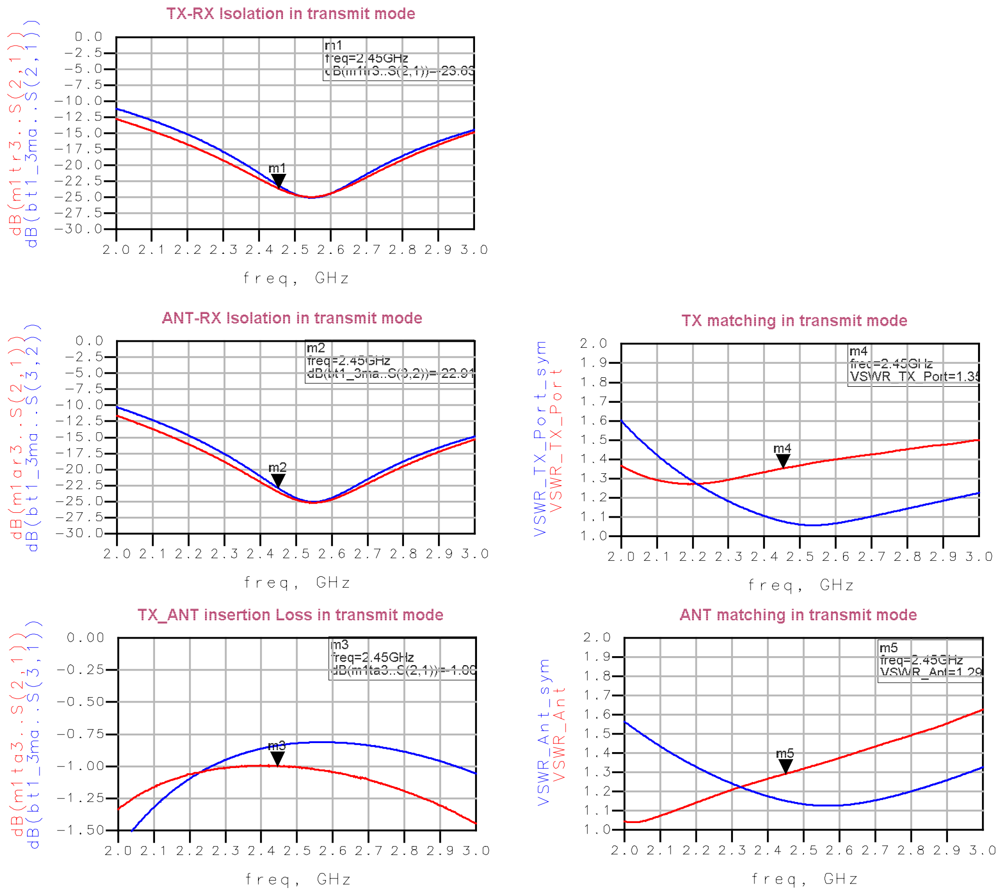

Figure 9; Results in TX mode; red curves are measurements, blue curves are the simulated ones.

Remark: *Loss and Isolation results are all including approximately 0.2 dB loss of the SMA connectors which were used to fed the RF signals through the design. this has a great effect on the Insertion-Loss results.*

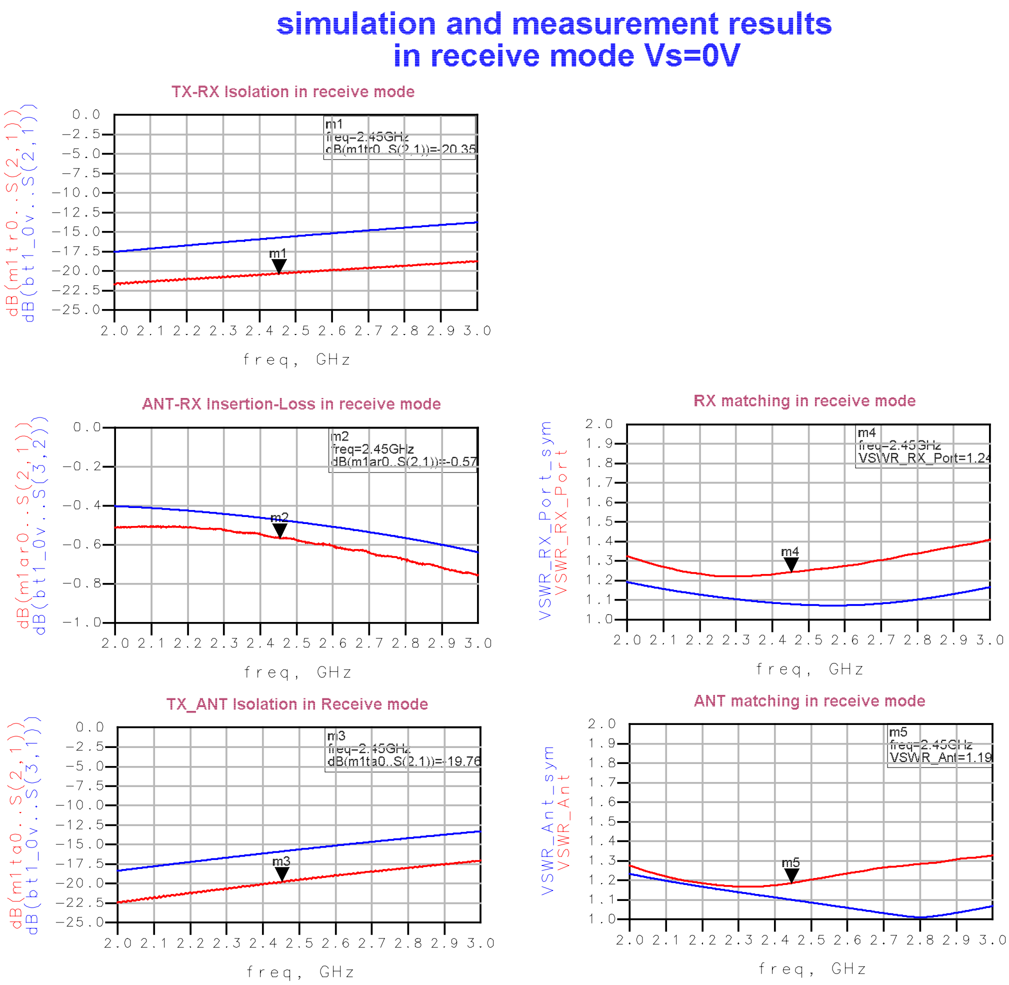

Figure 10; Results in RX mode; red curves are measurements, blue curves are the simulated ones
***Remark:** Loss and Isolation results are all including approximately 0.2 dB loss of the SMA connectors which were used to fed the RF signals through the design. this has a great effect on the Insertion-Loss results.*

Recommendations.

1 In this design the BAP51-02 was used because it's designed for switching applications related to Insertion Loss and Isolation. When for instance a better IM distortion is recommended it's better to use the BAP64-02 of Philips Semiconductors.

2 As you can see the $\lambda/4$ section still needs a lot of boards space. This section could be replaced by a lumped element configuration, which results in an extra boardspace reduction.

References:

1; Gerald Hiller, "Design with PIN diodes", App note APN1002 Alpha industries inc.
2; Gerald Hiller, "Predict intercept points in PIN diode switches", Microwaves & RF, Dec. 1985.
3; Robert Caverly and Gerald Hiller, "Distortion in PIN diode control circuits" IEEE Trans.Microwave theory tech.,May 1987.