Nova Scientia
Revista de Investigación de la Universidad De La Salle Bajío

Revista Electrónica Nova Scientia

Análisis de desempeño de conmutadores de microondas tipo serie-paralelo y TEE de diferentes materiales semiconductores para comunicaciones Satelitales
Performance analysis of series-shunt and TEE types of microwave switches of different semiconductor materials for Satellite communications

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Resumen

Se presenta un análisis de desempeño de conmutadores de microondas compuestos, de una entrada y una salida (SPST), diseñados con diodos p-i-n tipo masa con diferentes tipos de materiales semiconductores para las bandas de frecuencia Ku y Ka. Las dos configuraciones de conmutadores compuestos más comunes son aquellos con diodos p-i-n ubicados en diseños serie-paralelo y serie-paralelo-serie (TEE) y aquí son analizados utilizando materiales semiconductores de Si, GaAs, GaN-WZ, GaN-ZB, GaSb, InP y SiC. Se presenta la metodología utilizada en los cálculos de resistencia serie y capacitancia de unión en los diodos p-i-n con el propósito de calcular los parámetros de desempeño propios de cada dispositivo conmutador. Estos parámetros son pérdida de inserción y aislamiento. Los conmutadores de tipo serie-paralelo, exceptuando el conmutador basado en diodo p-i-n de SiC-6 H, exhiben pérdidas de inserción menores a 0.2 dB y aislamiento hasta 41dB a la frecuencia de operación de 12 GHz. El conmutador diodo p-i-n tipo TEE con base en GaN-ZB tiene la mejor respuesta de pérdida de inserción menor a 0.23 dB y aislamiento hasta 52 dB, a las frecuencias de operación de 12 GHz y 30 GHz. El conmutador compuesto con base en diodo p-i-n de GaSb alcanza el mejor desempeño a la frecuencia de 12 GHz. Los conmutadores de microondas con configuración TEE tienen respuestas satisfactorias para la frecuencia de 30 GHz.

Palabras clave: Conmutadores SPST, conmutadores de microondas Serie-Paralelo y TEE, diodos p-i-n, comunicaciones satelitales

Recepción: 09-12-2013 *Aceptación: 13-10-2014*

Abstract

A performance analysis of single-pole single-throw (SPST) compound microwave switches designed with bulk-type p-i-n diodes of different kinds of semiconductor materials for the Ku and Ka frequency band is presented. The two most common compound switch configurations are p-i-

n diodes mounted in either series-shunt or series-shunt-series (TEE) designs, and here analyzed using Si, GaAs, GaN-WZ, GaN-ZB, GaSb, InP and SiC semiconductor materials. The methodology used in the calculations to obtain serial resistance and junction capacitance existing in p-i-n diodes is presented in order to calculate the performance parameters proper to each switching device. These parameters are insertion loss and isolation. For the frequency operation of 12 GHz all the Series-Shunt switches, except to the switch based on 6H-SiC p-i-n diode, exhibited insertion losses as low as 0.2 dB and isolation up to 41 dB. The TEE-type p-i-n diode switch based on GaN-ZB has the best insertion loss response as low as 0.23 dB and isolation up to 52 dB on the operating frequencies of 12 GHz and 30 GHz. GaSb p-i-n diode compound switches reaches the best performance at 12 GHz of frequency. The TEE -configuration microwave switches are good for the operating frequency of 30 GHz.

Keywords: SPST Switches, Series-Shunt and TEE microwave switches, p-i-n Diodes, Satellite Communications

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Introduction

Switches on the base of p-i-n diodes are widely used in radio frequency systems that include phase shifters, attenuators, modulators and microwave switches. Before the 1990´s, switches on the base of p-i-n diodes had been favorites instead of FET switching devices [1]. Currently FET devices are still been developed due to their outstanding features; in the same way, phase shifter devices are often designed with p-i-n diodes which are implemented with antenna arrays for terrestrial and satellite applications. These antenna systems allow beam steering in a wider angular range and currently used in broadband communication systems [2].

Microwave p-i-n diode switches are characterized by low insertion loss, high power handling, high isolation switching and better microwave signal responses compared to the one using conventional diodes [1]. In practice it is usually difficult to achieve more than 40 dB isolation using a single silicon p-i-n diode, either in shunt or series, at microwave frequencies and there are proposals to use other semiconductor materials [3]. The impedance of a forward-biased p-i-n diode is a primary electrical parameter that determines performance in phase shifters, switches, and attenuator circuits.

Microwave and millimeter wave systems require low cost and high frequency solid-state components. The demand to keep system development cost low in this competitive environment has given important emphasis to using the well-defined solid-state component models in design and simulation of systems prior to fabrication and production [4].

In the design of microwave switches, where the diode control element is expected to switch between nearly open and nearly short-circuit impedances, it is shown that the impedance of these devices can change significantly as a function of frequency. Depending on the carrier lifetime and I-region thickness, the impedance can decrease, increase, or remain constant as the frequency changes.

P-i-n diode switches reach a high level of switching performance at high frequencies. One example is radio transceivers on radar systems designed with microwave switches operating in high-power conditions with minimum of insertion loss and power consumption [5]. In general, the figure of merit for power microwave switches is its impedance in forward bias state. The series resistance is dominated by the diode junctions and is directly proportional to the semiconductor breakdown voltage and inversely proportional to its critical electric field [6].

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Series-Shunt configuration has optimal responses in both insertion loss and isolation in a wide frequency bandwidth [7]. In general, both compound microwave switches here analyzed offer improved overall performance. On contrast, the added circuit complexity degrades the insertion loss response. Since all diodes are not simultaneously biased in one state or the other, there is an increase in bias circuit complexity. Although, improved performance is obtained using p-i-n diodes of different semiconductor materials.

Bulk-type p-i-n diodes are characterized by carrier lifetime greater than that of the epitaxial type p-i-n diodes. Because of this, bulk-type p-i-n diodes introduces low distortion, either harmonic distortion, intermodulation or cross modulation to the operation signal [8]. On the other hand, the epitaxial-type p-i-n diodes introduce high distortion to the signal. The carrier lifetime should be between 35 and 25 nanoseconds for epitaxial diodes or between 400 and 3000 nanoseconds for bulk-type p-i-n diodes. The intrinsic region of the epitaxial diodes has a thin thickness in comparison with the bulk-type p-i-n diodes [8].

For many years silicon has been used for microwave and RF semiconductor control devices, mainly for switch designs and variable attenuation devices to control high radio frequency signals [9]. Silicon band gap energy is the lowest of all the materials discussed in [10], this limits the performance of p-i-n diodes at high temperatures (<120 ° C) [11]. The Gallium Arsenide (GaAs) band gap energy is greater than that of silicon (Si), allowing GaAs p-i-n diode to have a higher breakdown voltage than a Si diode with the same intrinsic layer thickness. Furthermore, GaAs has direct recombination of minority carriers which limits the carrier lifetime to less than 10 nanoseconds, speeding up the charge displacement of the intrinsic region. Therefore, GaAs has a lower carrier lifetime and a reduced diffusion length, between 50 to 100 times, compared to Si [9].

SiC p-i-n diode achieves lower series resistance and better performance in power and switching speed, because this type of semiconductor can stand a higher breakdown electric field than Si and GaAs [12, 13]. Thus, a switch based on SiC p-i-n diodes achieves low insertion loss, even operating with high frequency signals. Although GaN semiconductor has a higher breakdown electric field than SiC, it was observed that GaN devices achieve lower breakdown voltages than expected [6]. Shunt type swiches designed with GaN p-i-n diodes can reach a better insertion loss at high operation frequencies compared to those designed on the base of Si [10].

The wide band gap semiconductors are used to design high-power switching devices, with lower losses in comparison to silicon switches. The main advantage of these semiconductors is their high critical electric field capacity (V/cm) [6]. An example of this is 4H-SiC semiconductor, which is characterized by a very wide band gap, high breakdown electric field, high rate of diffusion of saturation, high carrier mobility and high thermal conductivity [13, 14].

Performance parameters for series-shunt and TEE compound switches

Insertion loss and isolation have been used to evaluate the performance of microwave switches designed with p-i-n diodes with different semiconductor materials. The methodology used to analytically estimate insertion loss and isolation of these types of switches was presented in [12] and used in this work for series-shunt and TEE compound switches.

The theoretical series resistance of p-i-n diodes is calculated with:

$$R_T(f) = R_I + 2R_J(f) \quad (1)$$

where

$$R_I = \frac{kT}{qI_0}\frac{W}{L}\tanh\left(\frac{W}{2L}\right) \quad (2)$$

is the intrinsic resistance, and $R_J(f)$ defined as:

$$R_J(f) = \frac{KT}{qI_0}\beta\tanh\left(\frac{W}{2L}\right)\cos\left(\Phi - \frac{\theta}{2}\right) \quad (3)$$

is the frequency dependent junction resistance. L is the ambipolar diffusion length (=$\sqrt{D_{AP}\tau}$) that depends on the ambipolar diffusion coefficients for electrons (D_n) and holes (D_p), $D_{AP} = 2D_nD_p/(D_n + D_p)$. The p-i-n diode with i-region layer thickness, W, is characterized by a lifetime of minority carriers, τ.

The variables used in (2) and (3) are:

$$\beta = \frac{\sqrt{\left[\coth a(1+\cot^2 b)\right]^2 + \left[\cot^2 b(1-\coth^2 a)\right]}}{(1+4\pi^2 f^2\tau^2)^{1/4}(\coth^2 a + \cot^2 b)} \quad (4a)$$

$$\theta = \tan^{-1}(\omega\tau) \text{ with } \omega = 2\pi f \quad (4b)$$

$$\Phi = \tan^{-1}\left[\frac{\cot b\cdot(1-\coth^2 a)}{\coth a\cdot(1+\cot^2 b)}\right] \quad (4c)$$

$$a = \frac{W}{2L}(1+4\pi^2 f^2\tau^2)^{1/4}\cos\left(\frac{\theta}{2}\right) \quad (4b)$$

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$$b = a \tan\left(\frac{\theta}{2}\right) \tag{4d}$$

The junction capacitance of the p-i-n diode can be calculated with:

$$C_j = \frac{\varepsilon_0 \varepsilon_R \pi D^2}{4W} \tag{5}$$

where D is the p-i-n diode diameter.

Table 1 shows the series resistance and the junction capacitance in forward and reverse bias states, respectively.

Table 1: Series resistance and junction capacitance for p-i-n diodes designed with different materials

Material	R_T(Ohms)	Cj(pF)
GaAs	1.1	0.045
SiC-3H	1.1	0.043
SiC-4H	2.2	0.033
SiC-6H	3.0	0.033
GaN-WZ	1.2	0.033
GaN-ZB	0.8	0.030
InP	1.8	0.030

Single-pole single-throw (SPST) switches with p-i-n diodes mounted in both series-shunt and TEE designs are shown in figure 1.

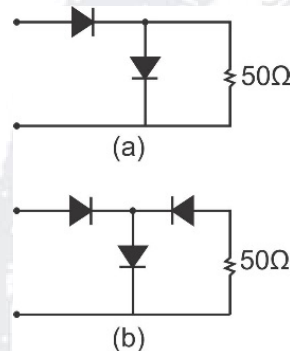

Fig. 1. SPST microwave switches with (a) series-shunt and (b) TEE compound switches [15]

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Once the series resistance and junction capacitance of p-i-n diodes are estimated, the performance parameters, insertion loss (IL) and isolation (I), can be calculated. Both are defined below.

For series-shunt SPST switch:

$$IL_{ss} = 10log\left[\left(1+\frac{R_T}{2Z_0}\right)^2 + \left(\frac{Z_0+R_T}{2X_c}\right)^2\right] \tag{6a}$$

$$I_{ss} = 10log\left[\left(1+\frac{Z_0}{2R_T}\right)^2 + \left(\frac{X_c}{2Z_0}\right)^2\left(1+\frac{Z_0}{R_T}\right)^2\right] \tag{6b}$$

For TEE SPST switch:

$$IL_{TEE} = 20log\left[1+\frac{R_T}{Z_0}\right] + 10log\left[1+\left(\frac{Z_0+R_T}{2X_c}\right)^2\right] \tag{7a}$$

$$I_{TEE} = 10log\left[1+\left(\frac{X_c}{Z_0}\right)^2\right] + 10log\left[\left(1+\frac{Z_0}{2R_T}\right)^2 + \left(\frac{X_c}{2R_T}\right)^2\right] \tag{7b}$$

Wherein Z_0 being the characteristic impedance of the transmission line, R_T is the p-i-n diode total series resistance and X_c its capacitive reactance.

Applying the methodology with the same characteristics of the diodes used in [16], good approximations in isolation and insertion loss for the SPST shunt type switch configuration are obtained. By considering the same parameters for the 4H-SiC diodes: 100 mA of forward current, 27 ns of carrier lifetime, 8×10^{18} cm^{-3} of acceptor concentration, 7×10^{15} cm^{-3} of donor concentration, $150\mu m$ of diameter and 50 V of reverse voltage, the insertion loss of 1.67 dB and an isolation of 54 dB are obtained. The values of junction capacitance and intrinsic layer thickness of 0.43 pF and 2.3 μm respectively, were estimated.

The p-i-n diodes considered in this work have the following characteristics: carrier lifetime of 45 nanoseconds, typical direct bias current of 10 mA, acceptor's impurity concentration of 1×10^{19} cm^{-3}, donor's impurity concentration of 8×10^{14} cm^{-3}, diode diameter of 71 micrometers, and reverse bias voltage of 45 V. These parameters are the same as the p-i-n diode used in [12].

Figure 2 shows the responses obtained by the microwave switches using p-i-n diodes designed with the semiconductor materials mentioned. This included responses of series and shunt type switches presented in [12] for comparison purposes.

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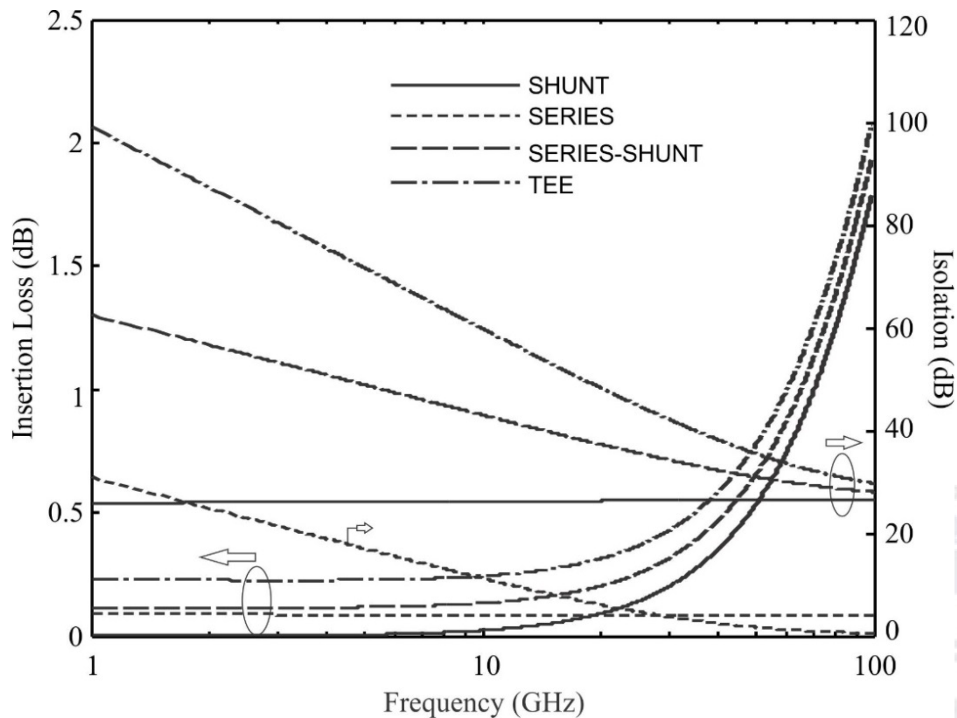
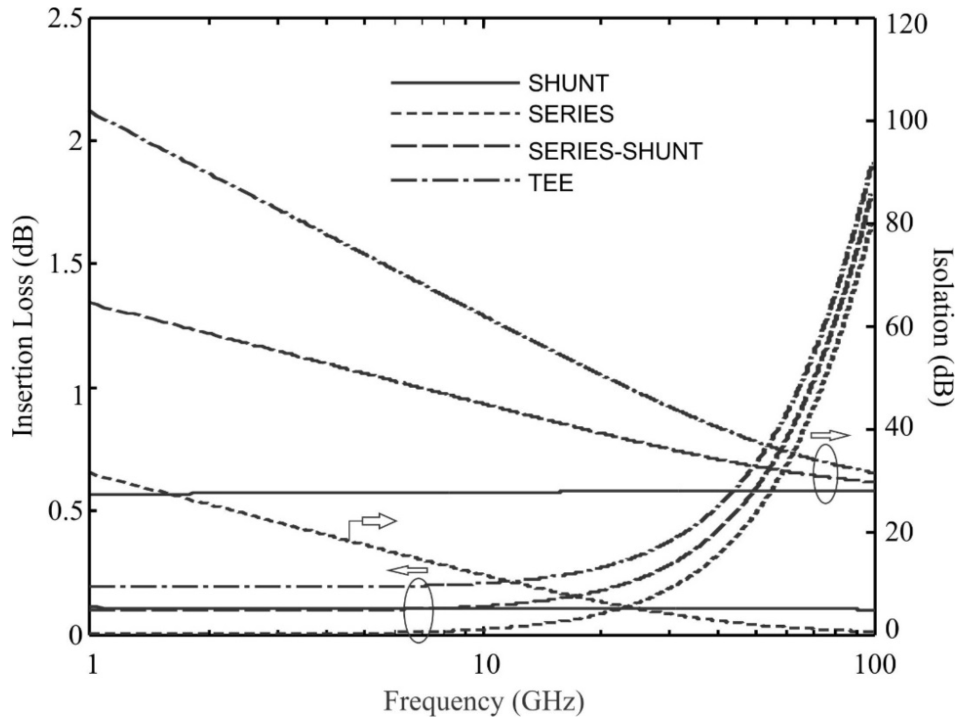
Results and Discussions

It can be seen that, at satellite communication frequencies, series-shunt and TEE compound switches offers the highest isolation response. These two types of switches have an isolation equation directly proportional to the operation frequency. See eqs (6b) and (7b).

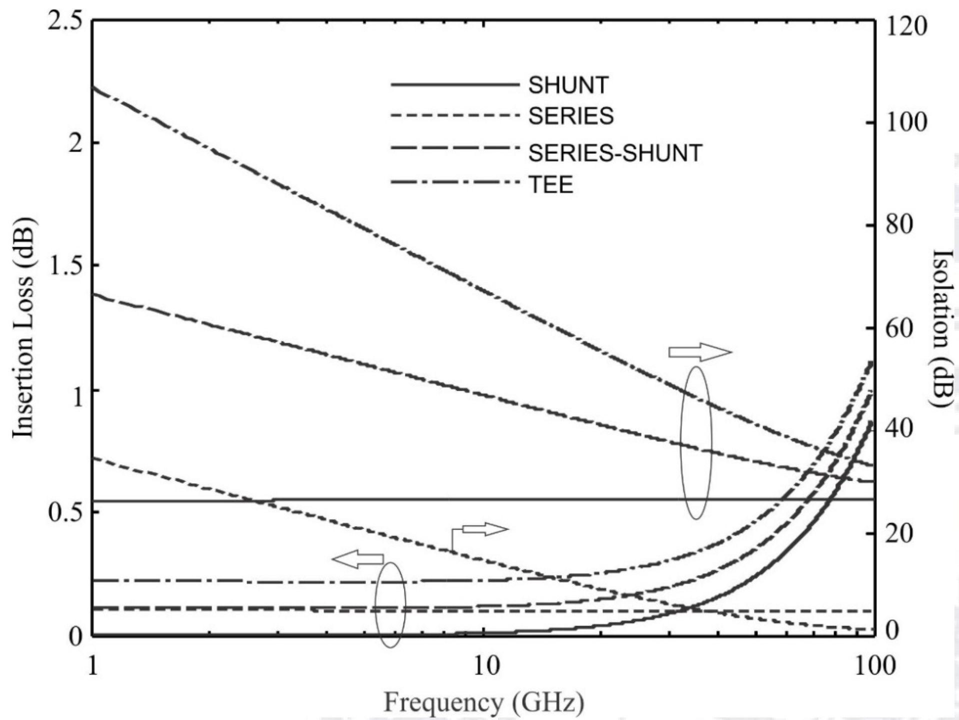
Insertion loss and isolation responses for four SPST switches using p-i-n diodes designed on different semiconductor materials for the frequency bands of 12 GHz and 30 GHz are presented in Figure 3.



(a)



(b)



(c)

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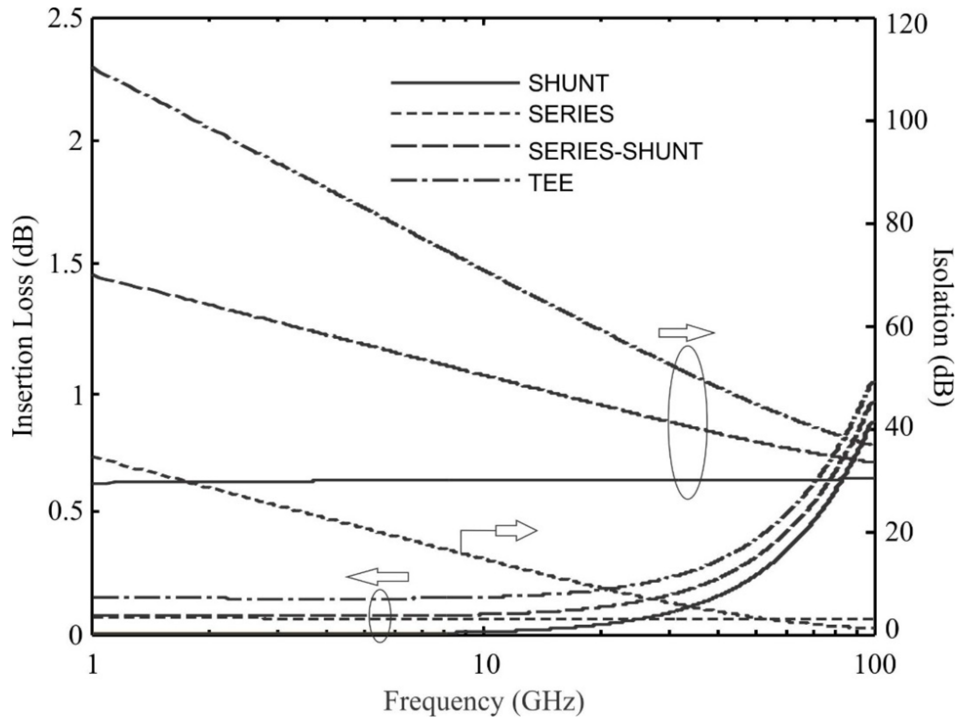
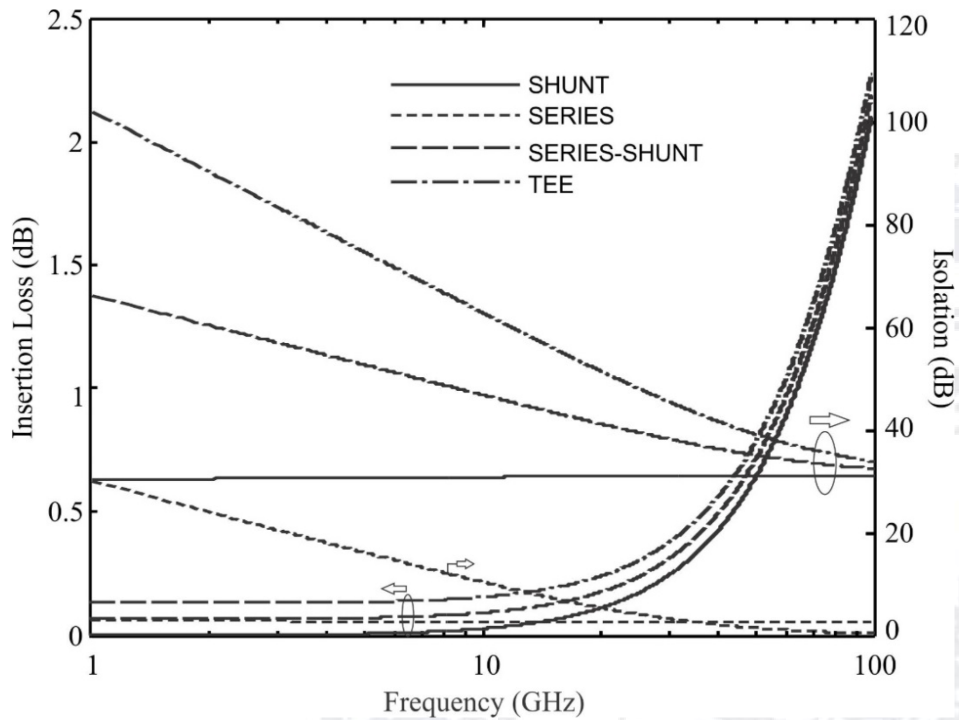


(d)



(e)

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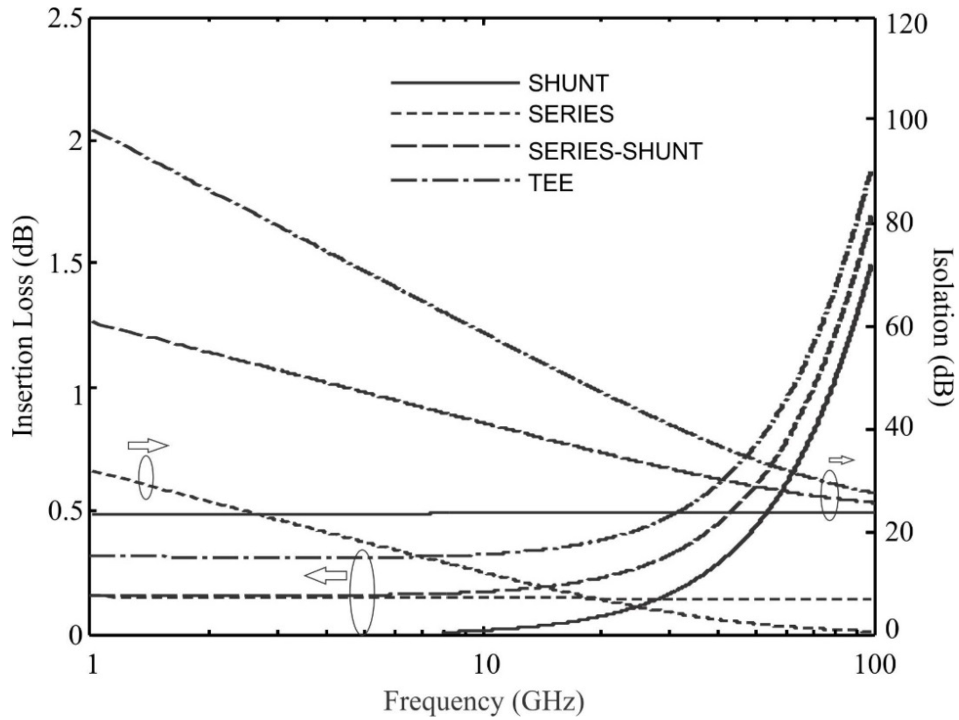
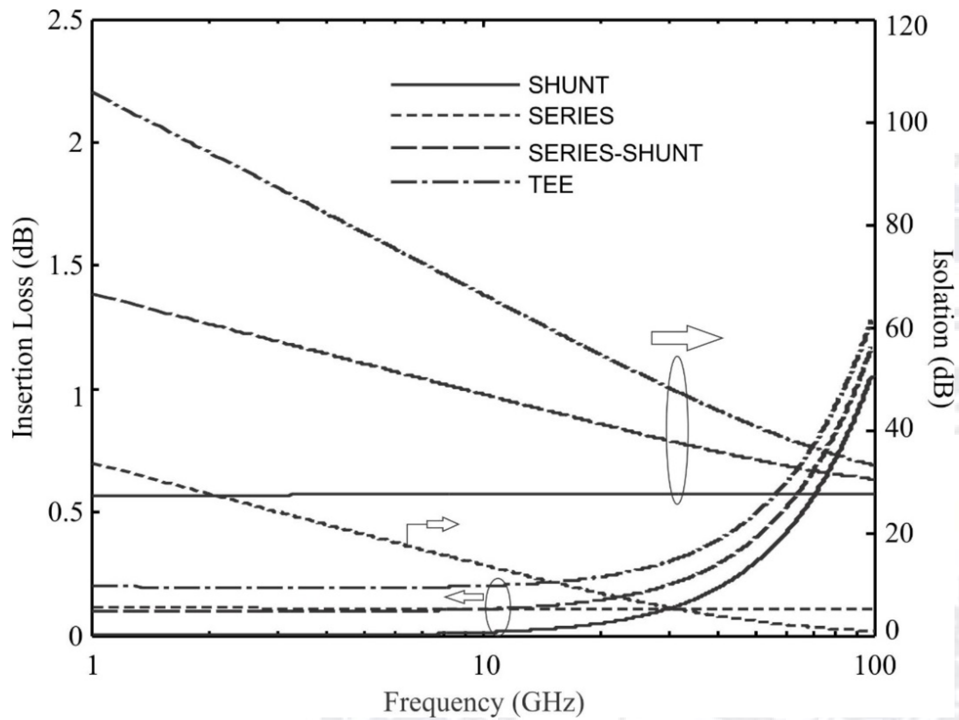


(f)



(g)

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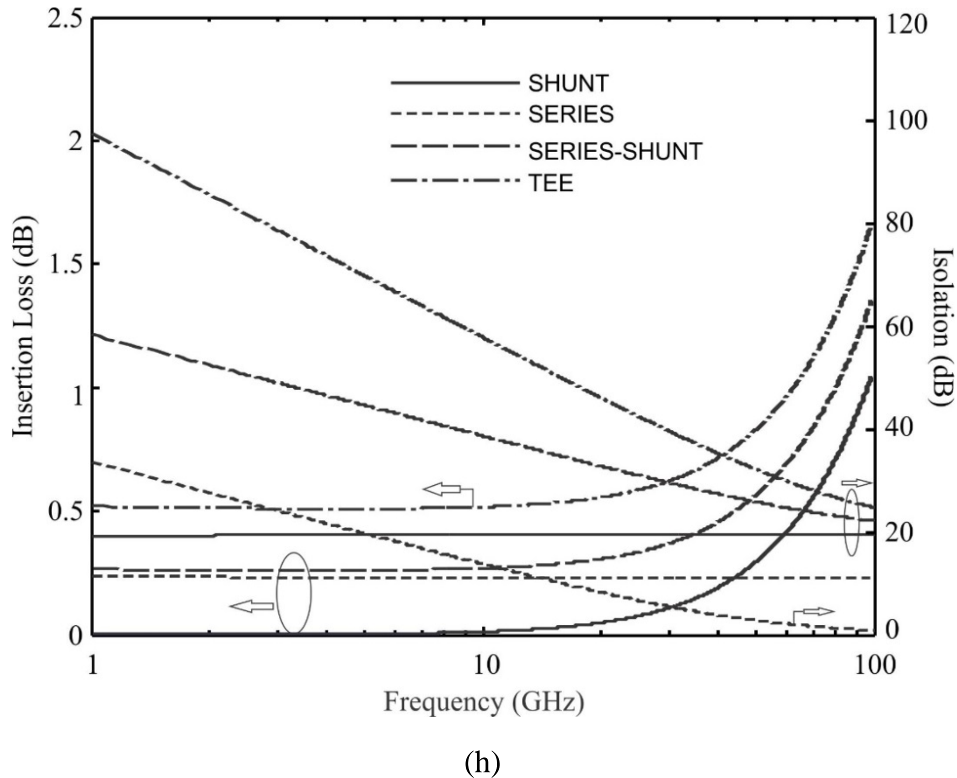
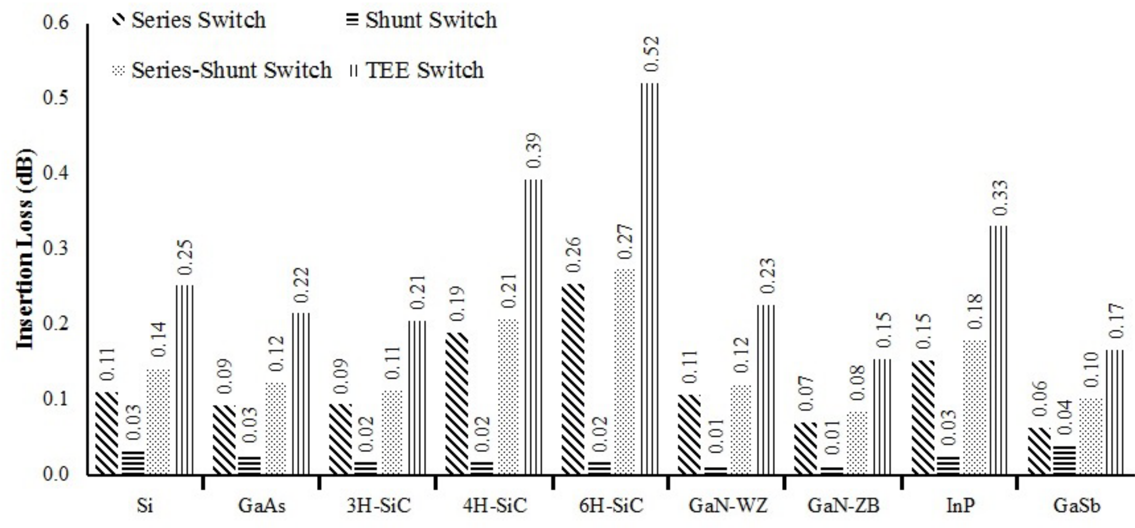


(h)

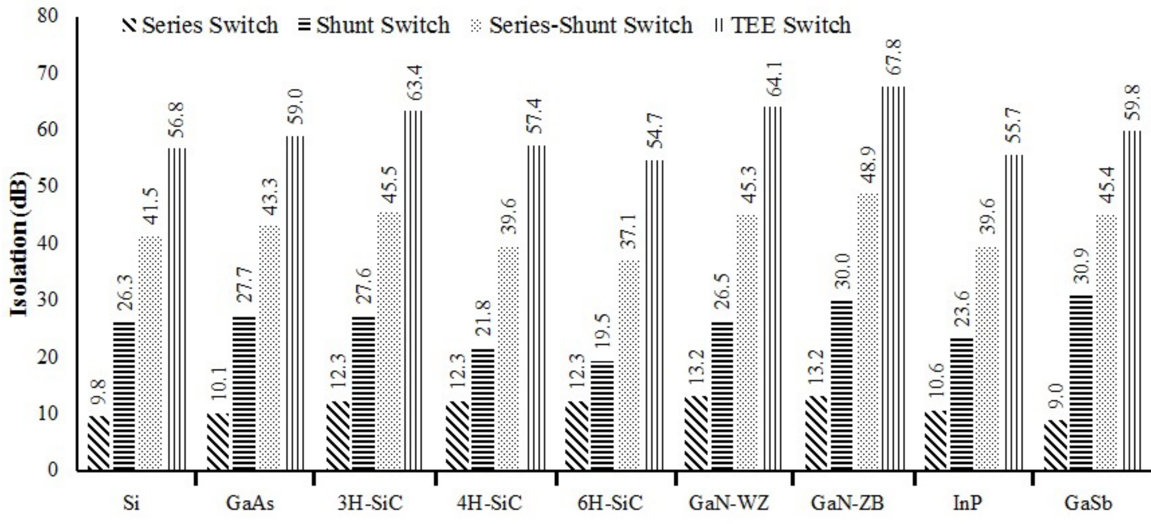
Fig. 2. Microwave switches based on p-i-n diodes designed with different semiconductor materials. With(a) Si, (b) GaAs, (c) GaN–WZ(d) GaN – ZB, (e) GaSb, (f) InP, (g) SiC–3H and (h) SiC–6H

At the operation frequency of 12 GHz, all series-shunt configurations, except the one designed with 6H-SiC, have insertion loss responses less than 0.21 dB with isolation greater than 39 dB. Its small junction capacitance yields to a higher signal rejection.

Although series -type switch with different semiconductor diodes have very good response of insertion loss (<0.15 dB), its corresponding responses of isolation do not exceed 9 dB, limiting to this frequency application. The TEE-type switch with GaN-ZB p-i-n diodes has good insertion loss and isolation responses, 0.15 dB and 67.8 dB respectively.



(a)

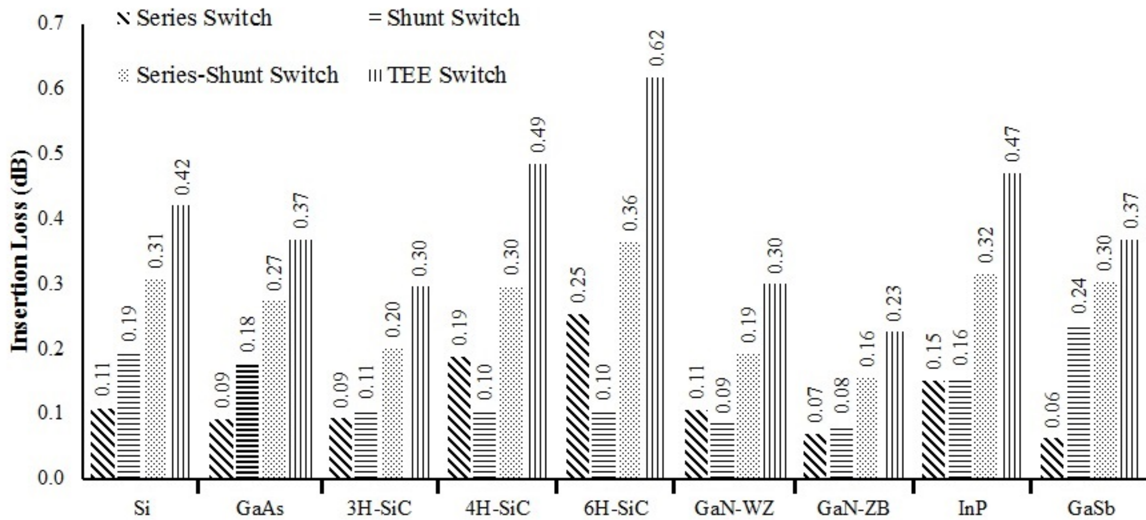


(b)

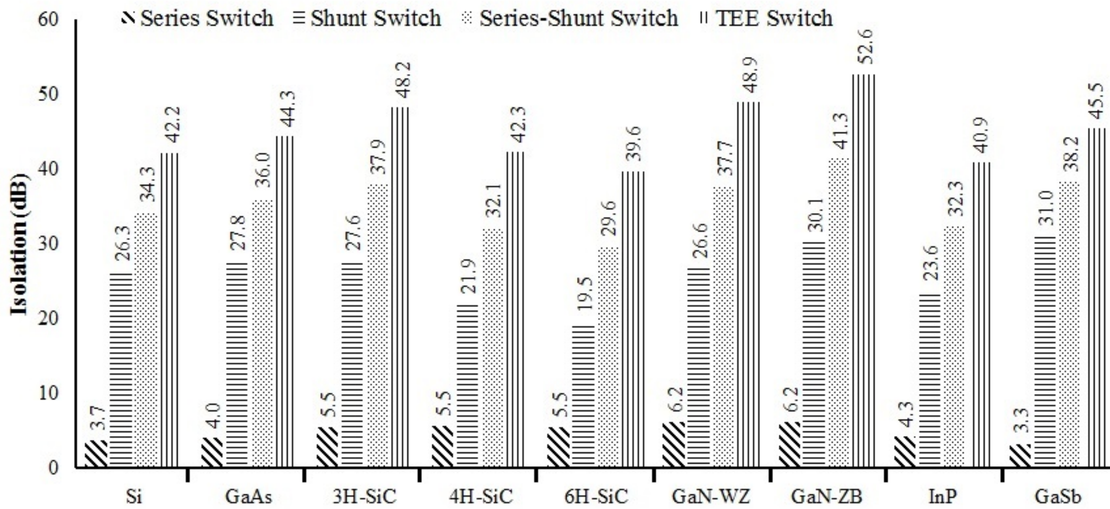
Fig. 3. (a) insertion loss and (b) isolation for switches designed with p-i-n diodes of different semiconductor materials for the operating frequency of 12GHz

At the operating frequency of 12 GHz the insertion loss response of the series-shunt –type switch is similar to the series configuration switch for all p-i-n diodes designs. The insertion loss response of all TEE –type switches are high due to the use of two p-i-n diodes in series to the transmission line.

Figure 4 shows the numerical results at the frequency band of 30 GHz. At this frequency, shunt-type switch designed with SiC p-i-n diodes (-3H, -4H, -6H) achieves an average insertion loss of 0.1 dB, the lowest result in comparison to other switches, and an optimal isolation between 19.5 dB and 27.6 dB.



(a)



(b)

Fig. 4. (a) Insertion loss and (b) isolation for switches designed with p-i-n diodes of different semiconductor materials for the operating frequency of 30GHz

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At 30 GHz of operation frequency, the insertion loss response of all TEE –type switches is greater than the one obtained at 12 GHz of frequency. For series p-i-n diodes, the presence of a parallel junction capacitance degrades isolation response between its terminals at this frequency.

Series-shunt type switches designed with GaAs, SiC-3H, GaN and InP semiconductor materials reach values of insertion loss between 0.16 dB and 0.27 dB, with optimal isolation between 32 dB and 38 dB. The TEE-type switch based on GaN-ZB p-i-n diode achieves the best response of insertion loss and isolation, 0.23 dB and 52.3 dB, respectively. That is because GaN-ZB has a low value of series resistance and junction capacitance in comparison to the other materials, see table 1.

For the shunt-type p-i-n diode switch, at the frequency of 30 GHz, the insertion loss response increases in comparison with that obtained at 12 GHz. Although, response of isolation of series-shunt and TEE -type switches are higher, and their insertion loss responses are greater compared to those of serial and shunt -type switches.

The isolation responses of all the p-i-n diode switches at 12 GHz of frequency are greater than those obtained at 30 GHz.

Conclusions

A numerical analysis of switching performance based on p-i-n diodes with different kinds of semiconductor materials for the frequency bands Ku and Ka widely used in satellite communications has been presented. Series-shunt type switches have optimal responses of insertion loss and isolation for operating frequency band of 12 GHz, and as the frequency increases, these performance parameters decreases. At this operation frequency, the series-shunt configuration fabricated from GaSb p-i-n diodes reaches the best performance, with insertion loss of 0.1 dB and an isolation of 45 dB. At the operating frequency of 30 GHz, the series-shunt configuration with GaN-ZB p-i-n diodes reaches an insertion loss and isolation of 0.16 dB and 41 dB, respectively.

TEE -type switches on the base of GaN-ZB p-i-n diodes reaches 0.15 dB of insertion loss and 67 dB of isolation at the operating frequency of 12 GHz. At the same time, this type of switches reaches 0.23 dB of insertion loss and 52 dB of isolation. The TEE -configuration microwave switches are recommended for the operating frequency of 30 GHz.

Acknowledgment

The authors acknowledge the support received through research projects SIP20141285 and SIP20141061.

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