A DC-60 GHz GaAs MMIC Switch Using Novel Distributed FET

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ABSTRACT

This paper presents the broadest-band distributed FET MMIC switch ever reported for millimeter-wave applications. The developed switch with the novel structure indicated an insertion loss of less than 1.37 dB and an isolation of better than 23.1 dB with monotonous increase up to 39.6 dB from DC to 60 GHz.

INTRODUCTION

For the communication and radar systems, T/R switches play an important role to control the RF signal flow. At millimeter-wave frequencies such as beyond 40 GHz, conventional FET switch circuits have employed the series FET configuration with a parallel combined inductor to obtain low insertion loss and high isolation [1]. However, the resonant frequency of this configuration is sensitive to the change of a pinched-off state capacitance in FETs. Moreover, this configuration is restricted to narrow-band applications. The so-called distributed switch circuits treated as an artificial transmission line which consist of the finite combination of a unit series inductor and a unit shunt discrete FET used as pinched-off state capacitor have been reported for broad-band applications [2][3]. However, the bandwidth of this type of switch was limited up to around 20 GHz due to the cut-off frequency of LC low-pass filter. Now, acceptable performance switch technology is emerging for millimeter-wave applications.

This paper describes the newly developed ultra-broadband millimeter-wave MMIC switch having the novel distributed FET structure. Measured excellent performances are successfully described by using lossless and lossy transmission line models for the on-state and the off-state switch circuits, respectively.

CIRCUIT DESIGN

We have developed the switch circuit using novel distributed FET (SCDF). The equivalent circuit of the developed shunt-SCDF is shown in Fig.1.

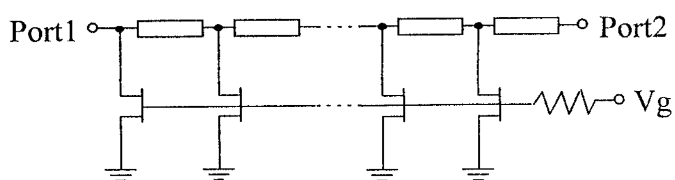

Fig.1 Equivalent circuit of shunt-SCDF

The shunt distributed FET is expressed as the infinite combination of a unit shunt FET of a 0.15 μm gate HJFET and a unit series transmission line of drain electrode. If the gate bias circuit is isolated with a sufficiently large value resistor, the unit FET in the open-channel state is expressed as a simple resistor, and in the pinched-off state approximately a simple capacitor. From our several examinations, the design parameters for the switch have been extracted. The unit resistance R (=1/G) of the open-channel state was 8 Ω, and the unit capacitance C_{FET} of the pinched-off state was 30 fF for the unit gate width of 100 μm. The inductance L and the capacitance C_{TL} for the unit 100 μm length of the transmission line composed of a drain electrode were 50 pH and 20 fF, respectively.

For the on-state of the shunt-SCDF, the equiva-

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circuit as the transmission line without transmission loss.

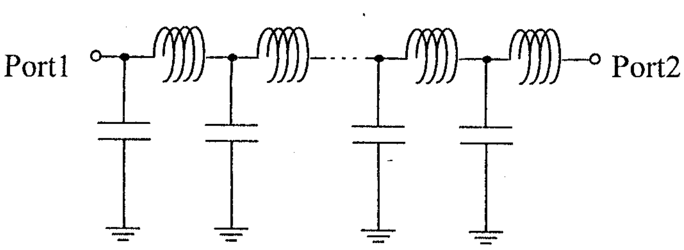

Fig.2 Equivalent circuit of shunt-SCDF for on-state

Thus, the insertion loss and the return loss of the shunt-SCDF are ideally derived as eq.(1) and eq.(2), respectively.

$$S_{21}^{ON} = \frac{2ZZ_0}{2ZZ_0 \cos\beta l + j(Z^2 + Z_0^2)\sin\beta l} \quad (1)$$

$$S_{11}^{ON} = \frac{j(Z^2 - Z_0^2)\sin\beta l}{2ZZ_0 \cos\beta l + j(Z^2 + Z_0^2)\sin\beta l} \quad (2)$$

$$\beta = \omega\sqrt{L(C_{TL} + C_{FET})} \quad (3)$$

$$Z = \sqrt{\frac{L}{(C_{TL} + C_{FET})}} \quad (4)$$

where Z_0 is the port impedance (usually 50 ohm), Z and l are the characteristic impedance and the physical length of the transmission line, respectively, β is the wave constant, L and C_{TL} are the inductance and the capacitance of the unit transmission line composed of a drain electrode, respectively, and C_{FET} is the capacitance of the unit FET for the pinched-off state. From eq.(1), it is clear that the insertion loss swings periodically as increasing frequencies. The insertion loss of the shunt-SCDF is only due to the impedance mismatching between the port and the switch. If Z is equal to Z_0, the insertion loss would be zero and the return loss would be infinity. From these equations, it can be expected that the shunt-SCDF will show no frequency limit if the transmission loss would be negligible.

For the off-state, the equivalent circuit of shunt-SCDF is shown in Fig.3. This is the same circuit as the lossy transmission line having the shunt conductance. Thus, the isolation of the shunt-SCDF is derived as eq.(5).

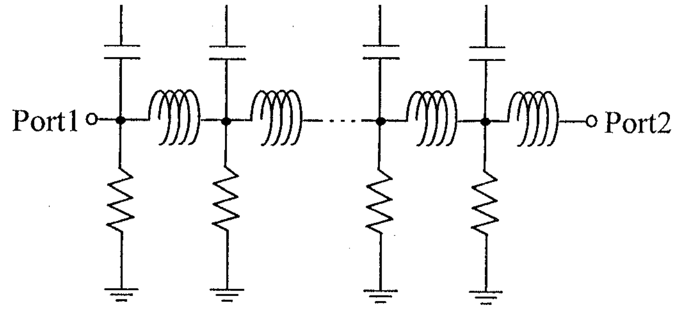

Fig.3 Equivalent circuit of shunt-SCDF for off-state

$$S_{21}^{OFF} = \frac{2ZZ_0}{2ZZ_0 \cosh\gamma l + (Z^2 + Z_0^2)\sinh\gamma l} \quad (5)$$

$$\gamma \equiv \alpha + j\beta \equiv \sqrt{j\omega L(j\omega C_{TL} + G)} \quad (6)$$

$$Z = \sqrt{\frac{j\omega L}{j\omega C_{TL} + G}} \quad (7)$$

where γ and α are the propagation constant and the attenuation constant, respectively, and G (=1/R) is the shunt conductance of the shunt-SCDF corresponding to the one of the transmission line. The calculation has been executed using above mentioned parameters and l=4 because of the 400 μm gate width FET.

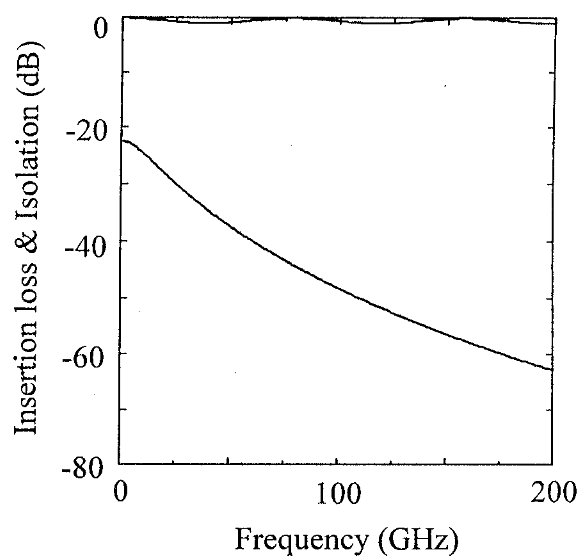

Fig.4 Calculated insertion loss and isolation of shunt-SCDF

The characteristic impedance for the on-state of the switch is calculated as 31.6 Ω from eq.(4). To improve the input matching, the characteristic impedance Z can be brought close to 50 Ω by decreasing the drain electrode line width.

Fig.4 shows the calculated insertion loss and isolation of the shunt-SCDF from DC to 200 GHz. It indicates high ON/OFF ratio which is better than 20 dB and higher isolation as increasing frequencies without significant degradation of the insertion loss from DC to 200 GHz. As seen later, these models explain the measured results very well in spite of a simple ones.

MMIC DESIGN AND FABRICATION

The shunt-SCDF was fabricated using 0.15 μm HJFET MMIC process for millimeter-wave applications with high reliability [4][5]. The top view of the developed shunt-SCDF MMIC is shown in Fig.5. The shunt-SCDF consists of only one 0.15 μm-gate FET with the gate finger of 400 μm which can be called the distributed FET. The RF signal input and output terminals are attached on the both ends of the drain electrode, respectively. The SCDF is obviously different from the previous distributed switch because of using the distributed FET which leads to no frequency limit. The size of SCDF is 0.4 mm× 0.07 mm.

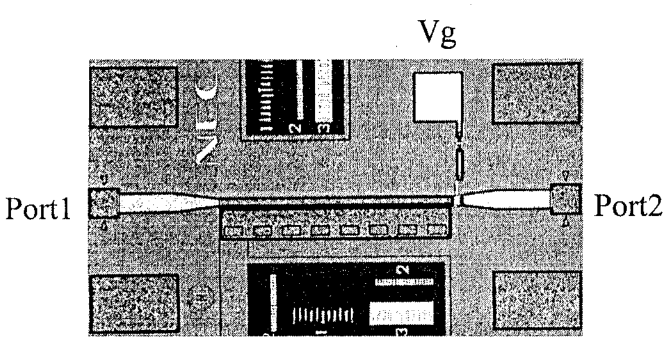

Fig.5 Top view of developed shunt-SCDF

MMIC PERFORMANCE

Fig.6 shows the measured insertion loss and isolation of the developed MMIC switch with calculated results. The measured curves indicated excellent agreement with calculated results. At 60 GHz, the insertion loss was 1.37 dB, and the isolation was 39.6 dB. The measured return loss of the developed MMIC switch with calculated result is shown in Fig.7.

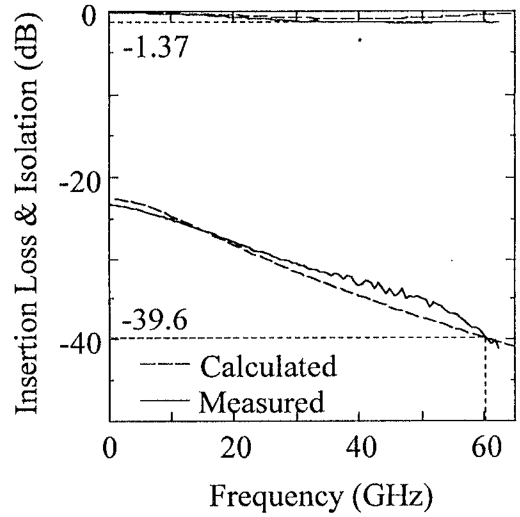

Fig.6 Measured and calculated insertion loss and isolation of developed shunt-SCDF

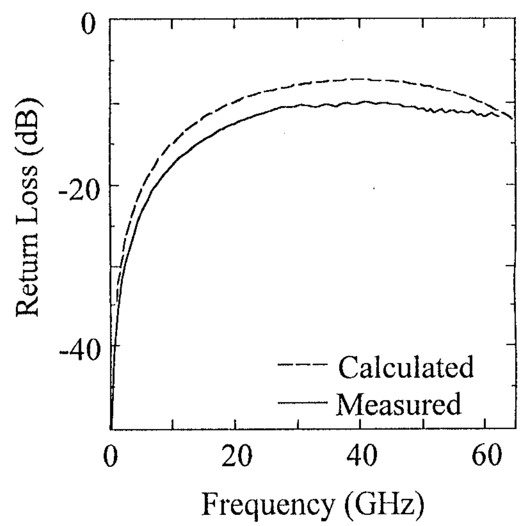

Fig.7 Measured and calculated return loss of developed shunt-SCDF

The measured curve also indicated good agreement with calculated one. From DC to 60 GHz, the return loss was better than 10 dB. Because the return loss and the insertion loss are due to the impedance mismatching between the port and the on-state shunt-SCDF as mentioned above, they would be improved by designing the impedance of the on-state shunt-SCDF to be the same as the port impedance. For instance, the improvement would be expected from refining the line widths of the drain electrode. Although the characteristics were measured only up to 60 GHz, the excellent performance is also expected beyond 60 GHz from the calculated performance.

CONCLUSION

We have developed the switch circuit using novel distributed FETs (SCDF) for millimeter-wave applications. The presented SCDF would successfully provide high performance MMICs for millimeter-wave communication and radar systems.

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