A High-Performance 40–85 GHz MMIC SPDT Switch Using FET-Integrated Transmission Line Structure

Junghyun Kim, *Student Member, IEEE*, Won Ko, *Student Member, IEEE*, Sung-Ho Kim, Jinho Jeong, *Student Member, IEEE*, and Youngwoo Kwon, *Member, IEEE*

***Abstract*—A compact ultra-broadband distributed SPDT switch has been developed using GaAs PHEMTs. An FET-integrated transmission line structure, where the source pad of the shunt FET has been integrated into the signal line while the drain has been grounded to a via-hole with minimum parasitic inductance, has been proposed to extend the operating bandwidth of the distributed switches. SPDT and SPST switches using this structure have been fabricated using a commercial GaAs PHEMT foundry. The SPDT switch showed low insertion loss ($<$2 dB) and good isolation ($>$30 dB) over an octave bandwidth from 40 to 85 GHz. At 77 GHz, the SPDT switch showed extremely low insertion loss of 1.4 dB and high isolation of 38 dB. The chip size was as small as 1.45×1.0 mm^2. To the best of our knowledge, this is among the best performance ever reported for an octave-band SPDT switch at this frequency range. SPST switch also showed the excellent performance with the insertion loss of 0.4 dB and isolation of 34 dB at 60 GHz**

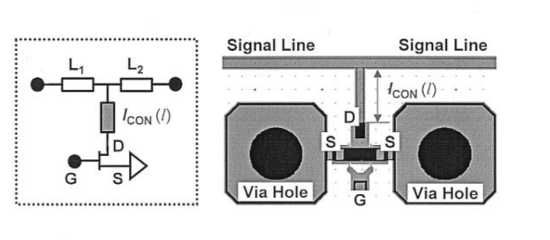
***Index Terms*—Distributed, GaAs pHEMT, SPDT, switch, transmission line, ultra-broadband.**

I. Introduction

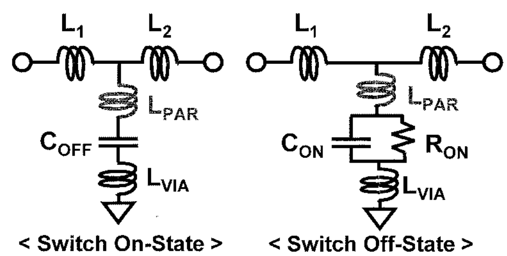
THE transmitter/receiver (T/R) switch is a key component for communication and radar system. For broadband systems, switches showing low insertion loss and good isolation over more than an octave band of frequencies is required. For millimeter-wave applications, FET switches are generally advantageous over p-i-n diode counterparts in terms of the monolithic integration capability with other transceiver components, fast switching speed, RF-isolated biasing and small power dissipation [1]. Especially, high-performance FET switches can facilitate highly integrated transceivers for 60 GHz communication systems and 77 GHz automotive radars.

For millimeter-wave applications, shunt switches have demonstrated superior insertion loss and isolation characteristics [3]–[6]. In order to increase the bandwidth of the shunt switches, distributed approach, where an artificial transmission line is formed by periodically loading the transmission line with the shunt diodes or FETs, has also been developed. A SPDT switch using the distributed shunt diodes realized by shorting the source and drain of the FETs showed 1.8 dB insertion loss together with 32 dB isolation from 50 to 70 GHz [4]. Distributed SPDTs using three-terminal shunt FETs have also been developed [5], [6]. However, when the shunt FET switches are realized with multiple-finger common-source FET structures, which are the standard FET structures offered by the commercial foundry, there is a need for an additional transmission line between the signal path and the shunt FET as illustrated in Fig. 1. This is to eliminate undesirable coupling effect between the signal line and ground via-holes. The length of this additional transmission line [l_{CON} in Fig. 1(a)] can be reduced somewhat by optimizing the via-hole layout. However, there is a physical limit and the finite length of this line introduces parasitic inductance [L_{PAR} in Fig. 1(b)], thereby reducing the bandwidth of the capacitively-loaded artificial transmission lines. There have been attempts to solve the problems either by resonance [5] or impedance transformation [6]. However, these approaches eventually restrict the operating bandwidth of the distributed FET switch, and result in large chip size.

In this work, compact broadband SPST and SPDT switches have been developed using improved shunt FET structures, where the pads of the FETs are integrated into the transmission lines to minimize the parasitic effects. Using the standard



(a)



(b)

Fig. 1. (a) Schematic and (b) equivalent circuit for the switch-on/off state of a conventional shunt switch using two-finger common-source FETs.

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The authors are with the Center for 3-D Millimeter-Wave Integrated Systems, School of Electrical Engineering, Seoul National University, Seoul 151-742 Korea (e-mail: ykwon@snu.ac.kr; jh4144@snu.ac.kr).

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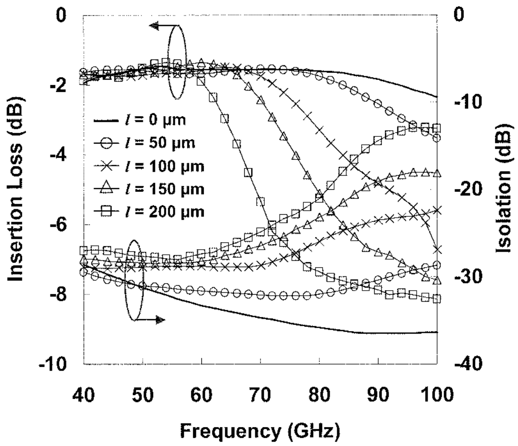
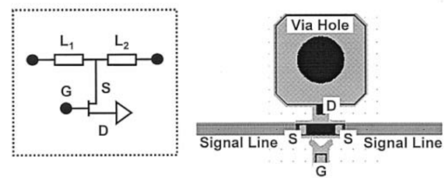


Fig. 2. Simulated insertion loss and isolation of the 5-section distributed shunt switch as the connecting line length ($l_{\rm CON}$) is increased from 0 to 200 μm.



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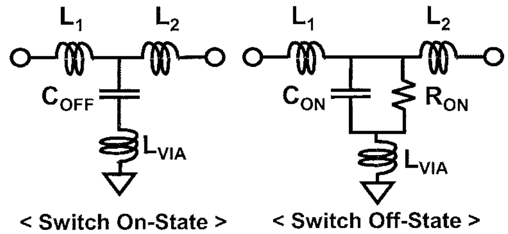


(b)

Fig. 3. (a) Schematic and (b) equivalent circuit of the switch-on/off state of the proposed unit cell using FET-integrated transmission line structure.

two-finger transistors offered by the commercial foundries, the SPDT switch showed very low insertion loss (<2 dB) and good isolation (>30 dB) over a wide bandwidth from 40 to 85 GHz. To our knowledge, this corresponds to the best performance reported for an octave-band SPDT switch at this frequency range.

II. Design and Fabrication

As shown in Fig. 1, the conventional distributed transistor switch using multiple-finger common-source shunt FETs requires a finite transmission line to be inserted between the signal line and the transistor, which introduces parasitic inductance, $L_{\rm PAR}$, to the shunt impedance. The shunt impedance in the on-state of the distributed switch is basically a series combination of a FET capacitance and a via-hole inductance; the via-hole inductance is typically on the order of 15 pH for the substrate thickness of 100 μm used in this work. The addition of $L_{\rm PAR}$ reduces the bandwidth of the artificial transmission line as shown in Fig. 2, which shows the simulated insertion loss and isolation characteristics of a conventional SPDT switch composed of five distributed shunt FETs for various line lengths ($l_{\rm CON}$). Line lengths ($l_{\rm CON}$) are varied from 0 μm to 200 μm in this simulation, corresponding to the parasitic inductance change from 0 pH to 100 pH. As the line length $(= l_{\rm CON}(l))$ is increased, the operating bandwidth of the distributed switch decreases rapidly. This problem should be solved in order to extend the operating frequencies of the distributed switch.

In this work, an improved shunt FET structure is proposed, where the source and drain has been reversed to facilitate ground connection to via-holes with minimum line lengths. Fig. 3(a) and (b) show the layout of the proposed unit cell using a two-finger FET and its equivalent circuit for ON and OFF state, respectively. The two source pads have been integrated as a part of the signal line, and connected to each other using an air-bridge. Small inductance from the air-bridge has been absorbed into the series inductance of the artificial transmission line. The drain pad is grounded using a via-hole. The connecting line to via-hole can in this way be minimized, resulting in negligible parasitic inductance. The structure can be easily extended to multiple-finger FETs.

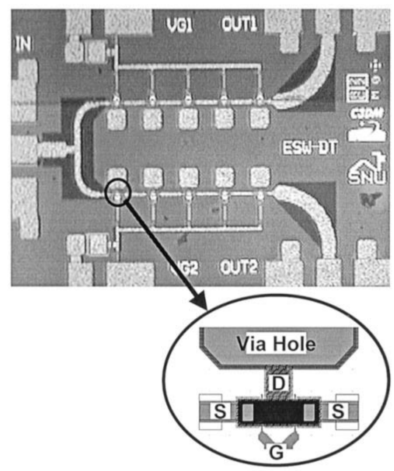
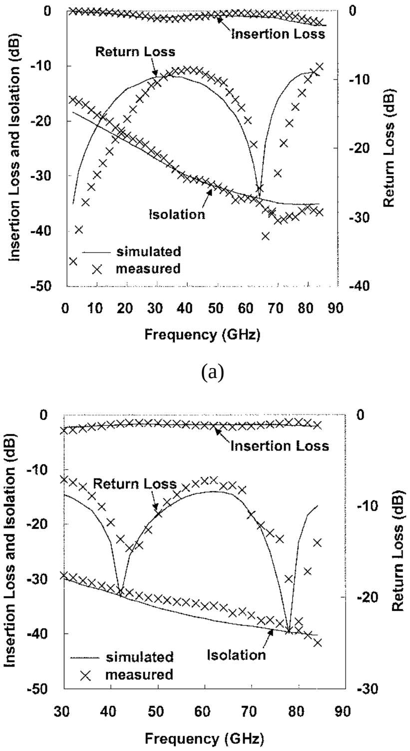


Fig. 4. Microphotograph of the fabricated SPDT MMIC. The chip size is 1.45 mm × 1.0 mm.

The SPDT switch consists of a tee junction and two distributed SPST switch branches connected to the tee junction using quarter-wavelength lines with a center frequency of 77 GHz. No impedance matching circuits or resonant circuits are used, resulting in a small chip size as well as broad bandwidth. Each distributed SPST switch is composed of five sections of FET-integrated transmission lines. The gate periphery of the shunt transistor is $2 \times 12.5\ \mu$m, and the unit finger width was matched to the width of the high-impedance inductive line (12.5 μm) in order to avoid the discontinuity effects. The on-state $({\rm Vg} = 0{\rm V})$ resistance and off-state $({\rm Vg} = -1.8\ {\rm V})$ capacitance of a unit transistor are 5∼6 Ω and 6∼7 fF, respectively. The gate bias is applied through a large resistor (500 Ω) to prevent RF signal leakage.

The switch MMIC has been fabricated using a commercial 0.15\ μm GaAs PHEMT foundry. The microphotograph of the fabricated SPDT switch is shown in Fig. 4. Overall chip size is only 1.45 mm × 1.0 mm. The SPST distributed switch, which is used at each branch of the SPDT switch, has also been fabricated and tested.



(b)

Fig. 5. Measured and simulated characteristics of (a) SPST and (b) SPDT distributed HEMT switches.

III. Measurements

RF performance of the fabricated MMIC HEMT switches has been tested up to 110 GHz using Agilent 8510XF network analyzer and on-wafer probing system. Simulated and measured results of both SPST and SPDT switches are shown in Fig. 5. The measured SPST switch shows insertion losses less than 1.8 dB up to 85 GHz. At 60 GHz, an extremely low insertion loss of 0.4 dB has been achieved together with high isolation of 34 dB. It is worthwhile to note that the large operating bandwidth (DC to 85 GHz) has been achieved using the FET-integrated transmission line structure thanks to the low-parasitic inductance. The measured SPDT switch showed the insertion losses of 1.6 $\pm$ 0.4 dB and isolation higher than 31 dB over a wide frequency range from 40 to 85 GHz. The return loss was better than 7.3 dB across the entire pass band. At 77 GHz, which corresponds to the frequency of the automotive radars, the insertion loss was as low as 1.4 dB and the isolation was higher than 38 dB together with 15 dB return loss. To the best of our knowledge, this is among the best results for 77 GHz SPDT switches. Fig. 5 also shows a good agreement between the measurement and simulation.

Table I summarizes the reported characteristics of the SPDT switches at mm-wave frequencies. The distributed switch of this work shows state-of-the-art overall performance in terms of bandwidth (40$\sim$85 GHz, 1:2.1), insertion loss ($<$2 dB), isolation ($>$30 dB) and chip size (1.45×1.0 mm^2).

TABLE I
Summary of the Reported Characteristics of the Broadband SPDT Switches at MM-Wave Frequencies

Reference	*[2]	*[3]	*[4]	*[5]	*[6]	This Work
Design Configuration	Distributed (1) Schottky diode (2) PIN diode	2 shunt MESFET's	Distributed 5 shunt diodes (by source-drain shorted HEMT)	2 shunt HJFET's (using resonant circuit)	2 shunt HEMT's (using impedance transformation circuit)	Distributed 5 shunt HEMT's (by FET-integrated transmission line structure)
Operating Bandwidth (GHz)	(1) 69-85 (2) 63-83	56-64	50-70	57-61	53-61	40-85
Insertion Loss (dB)	(1) <2.0 (2) <2.5	<3.2	<1.8	<5	<4	<2
Isolation (dB)	(1) >20 (2) >25	>23	>32	>25	>30	>30
Chip Size (mm^2)	(1) 2.6 x 1.3 (2) 3.3 x 1.7	0.8 x 2.45	2.65 x 1.33	3.3 x 1.7	2.0 x 1.0	1.45 x 1.0

* References

IV. Conclusions

A wideband SPDT switch has been developed using a commercial PHEMT foundry. The operating bandwidth of the distributed PHEMT switch has been extended to 85 GHz using a new FET-integrated transmission line structure, where the source pad has been integrated into the signal line and the drain has been grounded to a via-hole with minimum section of transmission lines. The circuit does not rely on any resonant circuits or impedance transformers, resulting in a small chip size (1.45×1.0 mm^2) and ultra broad bandwidth. The SPDT switch showed a low insertion loss ($<$2 dB) and good isolation ($>$30 dB) from 40 to 85 GHz. At 77 GHz, the SPDT switch showed excellent performance of 1.4 dB insertion loss and 38 dB isolation. The SPST switch, which were used at each branch of the SPDT switch, also showed a very low insertion loss of 0.4 dB together with an isolation of 34 dB at 60 GHz. The SPDT switch of this work can be effectively used for a wide variety of applications including 60 GHz and 77 GHz T/R switches.

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