A Low-Voltage, High-Power T/R-Switch MMIC Using LC Resonators

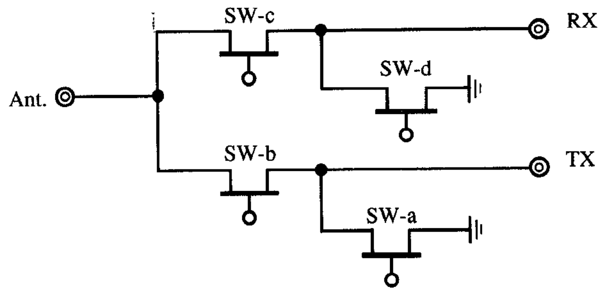
Tsuneo Tokumitsu, *Member, IEEE,* Ichihiko Toyoda, *Member, IEEE,* and Masayoshi Aikawa, *Member, IEEE*

***Abstract*—A novel T/R switch is proposed for high-power/low-distortion operation at a low control voltage. LC-resonant switches composed of inductors, capacitors, and switch FET's are incorporated in TX and RX arms to provide a reverse control scheme that removes the rf-voltage limitation in the transmit mode. A 1.9-GHz LC-resonant T/R switch MMIC with a total FET periphery of 3.36 mm exhibits 3rd IMR less than −40 dB for an input power up to 31 dBm when controlled at 0 V/−2 V. This MMIC occupies an area as small as less than 2×2 mm. This will make it possible to implement advanced T/R-switches at PCS and ISM frequencies below 5 GHz.**

I. Introduction

The maximum transmit power, $P_{\max}$, and linearity of conventional series/shunt FET T/R switches are severely limited by the rf-voltage swing across the drain/source and gate of the off-state FET's: SW-a and SW-c [1]–[4]. A typical diagram of these switches is provided in Fig. 1(a). Given this limitation, high-power/low-distortion switch operation can only be achieved by higher breakdown-voltage FET's, higher control-voltage, and rf-voltage distribution by stacking FET's [5]–[8]. However, these approaches also face serious limitations. First, system requirements for lower supply voltage in handheld communications equipment make it considerably more difficult to achieve the required transmit power with conventional series/shunt FET T/R switches. This is because maximum transmit power decreases rapidly due to rf-voltage limitations below a control voltage of 3 V. Second, impedance transformation is a technique that places the switch FET at a lower impedance point and thus reduces the voltage stress on the device, but occupies a considerably large area in the MMIC implementation for numerous commercial bands below 5 GHz [9].

Given these limitations, this paper introduces a unique and practical solution for high-power/low-distortion T/R switching at much lower control voltages. The circuit uses novel FET-switchable LC-resonant circuits. These replace SW-a and SW-c, shown in Fig. 1(a), with a LC-resonant circuit composed of spiral inductors, MIM capacitors, and switch FET's. The significant advantage of the FET-switchable LC resonators is that they provide a reverse control scheme: The LC resonator is "off" when the switch FET's are "on," and vice versa. Thus, the reverse control scheme permits all switch FET's to be in the on-state for the transmit mode. Accordingly, applied voltage across the drain/source and gate is nearly zero. This effectively removes the rf-voltage limitation in conventional T/R switches. The $P_{\max}$ and linearity in power handling characteristics can then be significantly enhanced by increasing the FET gate-widths. A 1.9-GHz T/R-switch MMIC using LC resonators has been successfully designed and fabricated, attaining the 3rd IMR of less than −40 dB for transmit power greater than 1 W at control voltages as low as 0 V/−2 V.



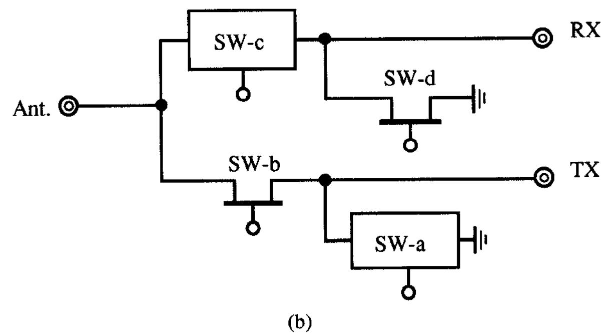


Fig. 1. Typical T/R-switch schemes for (a) conventional and (b) both proposed and conventional.

II. Maximum Transmit Power Comparison

FET's states for the proposed and conventional T/R switches in the transmit mode are compared in Table I, using a common equivalent circuit scheme (Fig. 1(b)) for both T/R switches. The difference between them is that the proposed T/R switch includes only on-state FET's, while conventional ones have both on- and off-state switch FET's.

The maximum transmit power, $P_{\max}$, for the conventional and proposed T/R switches are respectively defined by

$$\text{Conventional: } P_{\max} = \frac{2[n(V_c - V_p)]^2}{Z_0}$$

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The authors are with the Radio Systems Laboratory, NTT Radio Communication Systems Laboratories, Kanagawa 238-03, Japan.
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TABLE I
STATE OF THE SWITCH FET'S IN SW-'S FOR THE TRANSMIT MODE

SW-a & c / T/R switches	State of FET's in SW- a	b	c	d	Required FET perf.
Proposed LC resonant T/R sw.	ON	ON	ON	ON	High-Current
Conventional FET T/R sw.	OFF	ON	OFF	ON	High Voltage & Current

[7], [8], and

$$\text{Proposed: } P_{\max} = \frac{Z_0}{2}\left(\frac{I_{\text{dss}}}{Q_L}\right)^2,$$

where V_p is the pinch-off voltage of the switch FET, V_c is a control voltage for off-state FET's, n is the number of FET cells stacked in SW-a and SW-c, and I_{dss} and Q_L are, respectively, the saturation current of the FET's in the LC-resonant circuit and the loaded Q of the T/R switch in the transmit mode. Term Z_0 is the system impedance.

Fig. 2 shows $P_{\max}$ for recently reported conventional series/shunt T/R switches, where it is measured at a 1-dB gain compression point. The white squares [1]–[4], black squares [5]–[7], and white triangle [8] indicate the T/R switches using single-FET's, stacked-FET's, and multigate-FET's, respectively, for SW-a and SW-c. Shadowed curves are the calculated $P_{\max}$ for a T/R switch constructed with single-FET's ($n = 1$) and stacked-FET's ($n = 5$), where V_p is between -1 and -2 V. To transmit 1 W, for example, a control voltage of at least 6 V is necessary for $n = 1$, and n of at least 5 is necessary for control voltage as low as 2 V. However, the stacked FET number, n, is practically limited below 3 because increase in series resistance in SW-a and SW-c considerably degrades T/R switch performance. Fig. 3 compares $P_{\max}$ for the proposed and conventional T/R switches in 2-V operation. The gate width of each FET-cell in SW-a and SW-c, which is proportional to I_{dss}, is used as the parameter for comparison. The LC-resonant T/R switch increases the maximum transmit-signal voltage, at a control voltage of 0 V, in proportion to the FET-gate width. It also switches easily from transmit to receive mode at a control voltage of -2 V, as small as twice the V_p. In contrast, the conventional T/R switch provides constant transmit power for each n.

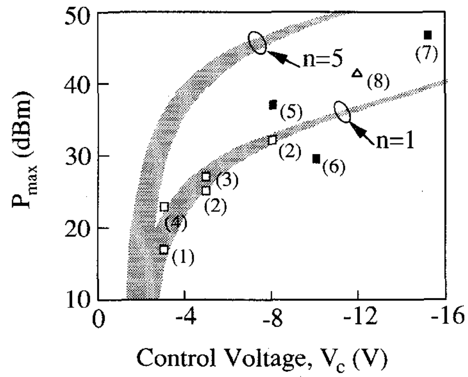


Fig. 2. Maximum transmit power versus control voltage for conventional FET T/R switches. The gray curves indicate the maximum transmit power calculated for T/R switches composed of single- and stacked-FET's (-1 V $> V_p > -2$ V).

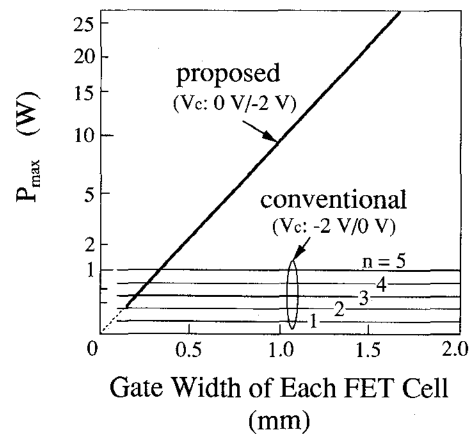


Fig. 3. Maximum transmit power comparison between the proposed LC-resonant T/R switch and conventional series/shunt FET T/R switches in 2-V operation, where $I_{\text{dss}} = 0.2$ A/mm, $V_p = -1$ V, and $Q_L = 0.44$.

TABLE II
PARAMETER RELATIONSHIPS FOR A SINGLE RESONANT FREQUENCY

Type	Relationship
(a)	$C_2 + C_S + C_1 C_S/(C_1 + C_S) = C_1$
(b)	$C_S + C_1^2/(C_1 - C_S) = C_1 L_1/L_2$
(c)	$C_2 + C_S = C_1$
(d)	$L_2(C_1 + C_S) = L_1 C_1$

III. T/R SWITCH DESIGN

A. LC Resonant Circuits

FET-switchable LC-resonant circuits are shown in Fig. 4(a)–(d). A pair of switching FET's (FET SW1 and SW2) are combined with inductors and capacitors. They are open ("off") between ports ① and ② when the switch FET's are in the on-state because of the parallel resonance of inductor L_1 and capacitor C_1. However, these circuits allow the signal to pass ("on") between ports ① and ② when the switch FET's are in the off-state because of the series resonance of inductor L_1 and capacitor C_2, shunted by C_S in Fig. 4(a) and (c) or the series resonance of capacitor C_1 and inductor L_2, shunted by C_S in Fig. 4(b) and (d). Capacitor C_S is the stray capacitance between the drain and source of the off-state FET. When the switch FET's are ideal and include no parasitics, the values of C_1 and C_2 are designed to be equal. However, since the stray capacitance, C_S is not negligible, capacitors C_1 and C_2 for each scheme are designed to satisfy the equations in Table II and cancel the effect of C_S in the resonant condition, where the resonant angle-frequency ω_0 is equal to $(L_1C_1)^{-1/2}$.

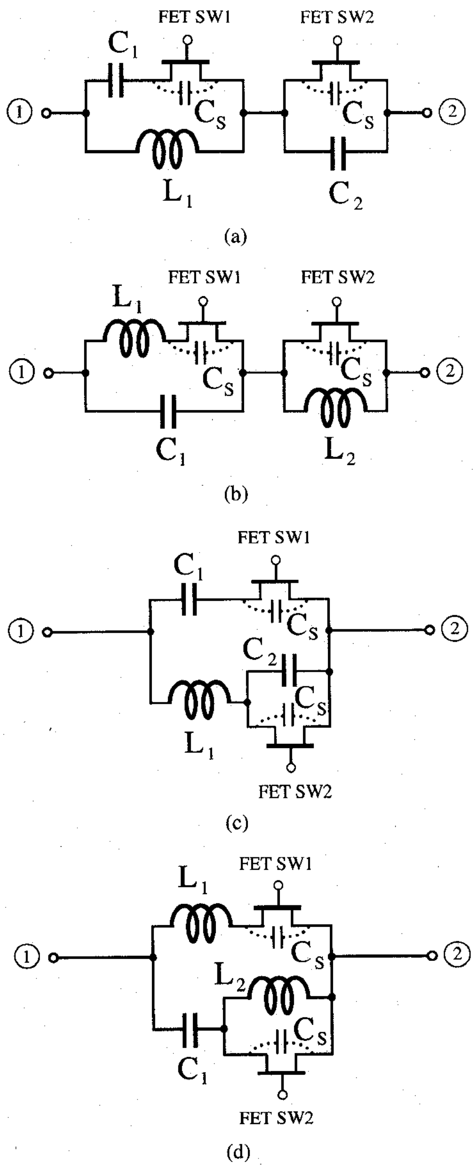


Fig. 4. FET-switchable LC-resonant circuit schemes.

B. T/R Switch

A T/R switch incorporating FET-switchable LC resonators of type (a) is shown in Fig. 5. These LC resonators are used as a shunt switch in the TX arm and as a series switch in the RX arm. The series switch in the TX arm and the shunt switch in the RX arm are both single-FET switches. The LC resonators are positioned in places where a large rf-voltage swing is applied in the transmit mode. Since all FET's in this mode are in the on-state ($V_c = 0$ V), the rf-voltage swing across the FET drain and source is negligibly small, i.e., the T/R switch operates in current mode free from rf-voltage limitation. A control voltage as small as twice the FET pinch-off voltage (V_p) is enough to switch from the transmit to the receive mode. Thus, as shown in Fig. 3, maximum transmit power can be increased by increasing the FET-cell periphery.

Design issues for the T/R switch include: limits on FET-gate width due to stray capacitance, C_S, and the bandwidth balance between the TX and RX arms. The maximum FET-gate width, $W_{g\,\max}$, for the LC resonator is determined by setting C_2 to zero in the parameter relationship for type (a) in Table II, as

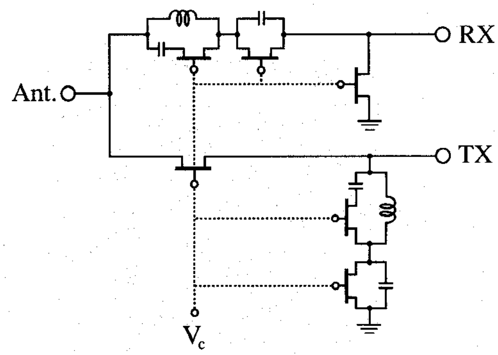


Fig. 5. Circuit scheme of a T/R switch incorporating FET-switchable LC-resonant circuits.

$$C_1 = 1.6C_S = 1.6C_{S0}W_{g\,\max}.$$

Therefore

$$W_{g\,\max} = \frac{C_1}{1.6C_{S0}} = \frac{1}{1.6\omega_0^2 L_1 C_{S0}}, \tag{1}$$

where ω_0 is the resonant angle-frequency ($(L_1C_1)^{-1/2}$) and C_{S0} is the drain-source stray capacitance per mm.

Bandwidth balance between the TX and RX arms is obtained when the loaded Q factors for both transmit and receive modes equal each other

$$\frac{\omega_0 L_1}{R_{\text{ind}} + 2Z_0} = \frac{2\omega_0 C_1}{2\omega_0^2 C_1^2 (R_{\text{ind}} + R_{\text{on}}) + 2/Z_0},$$

where R_{ind} and R_{on} are, respectively, the series resistance of inductor L_1 and on-state resistance of the switch FET. The left-hand side and the right-hand side of the equation indicate the loaded Q for the receive and transmit modes, respectively. A pair of the "off" state LC resonators are counted for the transmit mode. As the resonant frequencies for both modes are equal, the inductance value, L_1 can be derived from

$$(\omega_0 L_1)^2 = Z_0(2Z_0 - R_{\text{on}}) \approx 2Z_0^2. \tag{2}$$

Therefore, from (1) and (2), the maximum gate width for a 50-Ω system is represented by (3)

$$W_{g\,\max}(\text{mm}) = 1.4\,[f_0(\text{GHz}) \cdot C_{S0}(\text{pF/mm})]^{-1}. \tag{3}$$

The $W_{g\,\max}$ value is 0.7 mm when the resonant frequency, f_0, is 2 GHz, and C_{S0} is 1 pF/mm. By referring to Fig. 3, it can be seen that this gate width allows the T/R switch to transmit power up to 5 W. The smaller the C_{S0} is, the larger the FET that can be used for the LC resonator. Stray capacitance can be cancelled by connecting an additional inductive element, a method reasonably effective at higher frequencies to remove gate-width limitation.

Maximum FET-gate width for type (c) is obtained by the same procedure. It is 1.6 times larger than that for type (a). The other types of LC resonators, (b) and (d), are free from such limitations. However, the "on" state characteristics are

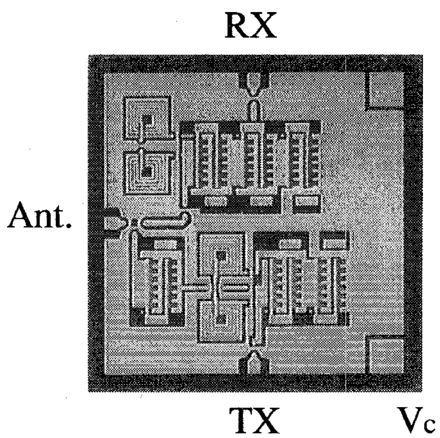


Fig. 6. Photograph of a fabricated LC-resonant T/R-switch MMIC.

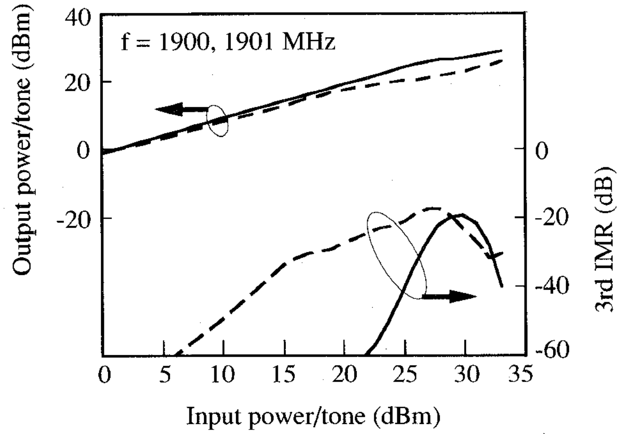


Fig. 7. Transmit-mode linearity comparison between the proposed LC-resonant T/R switch and a conventional T/R switch with stacked-FET's. The FET periphery of both switches was 2.88 mm.

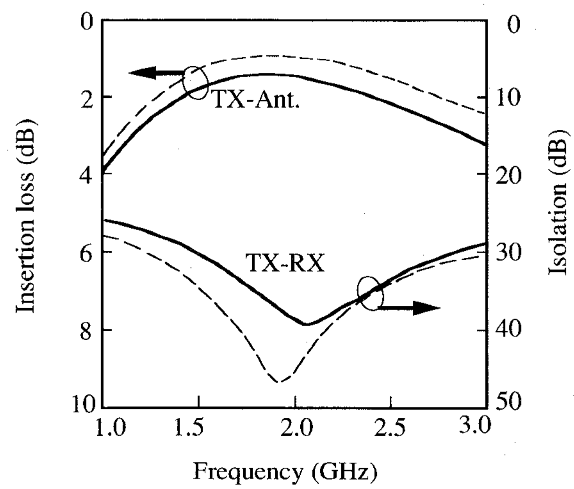


Fig. 8. Frequency response of the LC-resonant T/R switch in the transmit-mode (solid lines: measured; dashed lines: calculated). V_c is 0 V.

complex when C_S is close to or larger than C_1 because several resonations are observed in the scheme.

A T/R switch using the type (a) LC resonators was tested to confirm its potential. The results are reviewed in the next section.

IV. Measured Results

A 1.9-GHz LC-resonant T/R-switch MMIC, which handles an rf power of greater than 1 W at control voltages 0 V/−2 V, was fabricated using uniplanar MMIC technology [10]. Fabrication parameters were: $L_1 = 7$ nH; $C_1 = 1$ pF; $C_2 = 0.5$ pF; $C_{S0} = 0.625$ pF/mm; $R_{\rm on} = 2\ \Omega$ mm; and $I_{\rm dss} = 0.2$ A/mm. The loaded Q for the transmit mode was calculated as $\omega_0(L_1/2)/(2Z_0) = 0.44$.

A. Prototype T/R Switch

Six switching FET's, each having an FET periphery of 0.48 mm, were integrated with spiral inductors and MIM capacitors on a 2 ×2 mm GaAs chip, as shown in Fig. 6 [11]. The pinch-off voltage of the FET was −1 V. The total FET periphery was 2.88 mm. The Q factor of the spiral inductor at 1.9 GHz was between 10 and 15.

The linearity of the LC-resonant T/R switch in a two-tone measurement is compared with that of a conventional FET T/R switch in Fig. 7. Here, a pair of stacked FET's is used instead of the LC resonators for the case shown in Fig. 5. These T/R switches are controlled at 0 V or −2 V/0 V for the transmit mode. The LC resonant T/R switch (solid lines) is linear enough to exhibit 3rd IMR of less than −40 dB for a total input power to port TX (transmit power) of up to 28 dBm. The maximum transmit power for a single-tone reaches 31 dBm. In contrast, with the conventional switch (dashed lines), the linearity degrades above 16 dBm input power. The linearity of the RX arm depends on the negative control voltage; however, the linear power level over 0 dBm at $V_c = -2$ V is high enough for practical power levels received at port Ant.

Fig. 8 shows the measured and calculated frequency response of the proposed T/R switch in the transmit mode. An insertion loss of less than 1.5 dB, an isolation greater than 35 dB, and a return loss of better than 15 dB were measured between 1.8 and 2.0 GHz. Fig. 9 shows the frequency response in the receive mode measured at control voltages of −2 V (solid lines) and −5 V (gray lines). Very little difference between the two control voltages is observed. The difference between measured and predicted responses is considered to be due to the accuracy of the inductor model.

B. Improved T/R Switch

The measured maximum input power of 31 dBm to port TX is about 3 dB lower than that predicted in Fig. 3. The maximum transmit-power degradation is caused by the current through the series switch FET being nearly twice that through the switch FET's in the LC resonant circuit. This is because the loaded Q in the transmit mode is 0.44, as mentioned earlier. To show the full power potential of the LC resonator circuit, the FET-gate width of the series FET was doubled; other elements were not changed. The circuit scheme with the gate widths and an MMIC photograph are shown in Fig. 10. An output curve, which measures the maximum transmit power, becomes linear up to 34 dBm. The maximum input power in the two-tone measurement reaches 31 dBm as shown in Fig. 11. The

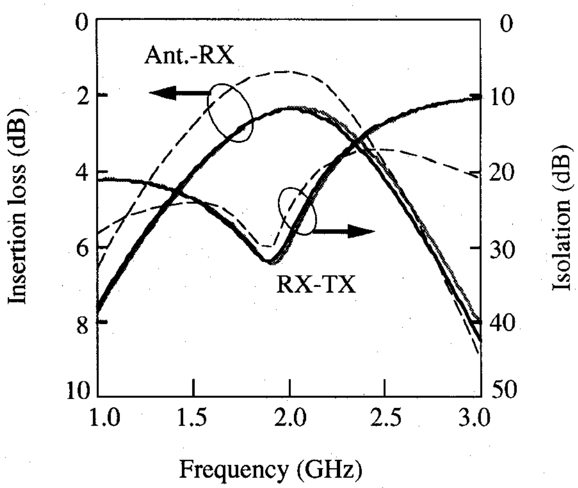
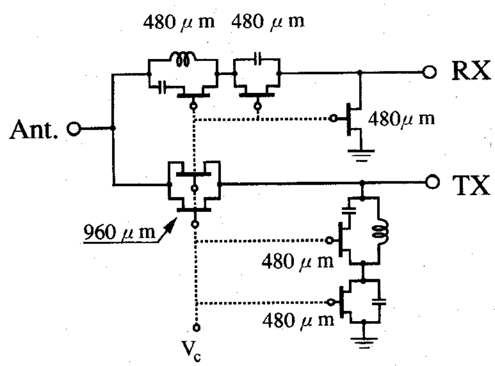
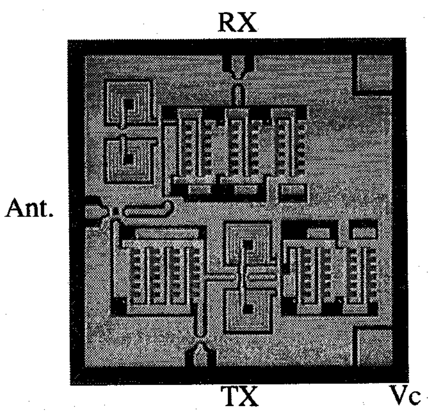


Fig. 9. Frequency response of the LC-resonant T/R switch in the receive mode. V_c is −2 V (black lines) and −5 V (gray lines). Dashed lines are calculated.



(a)



(b)

Fig. 10. (a) Circuit scheme and (b) the MMIC photograph of a LC-resonant T/R switch, which is improved in power-handling capability.

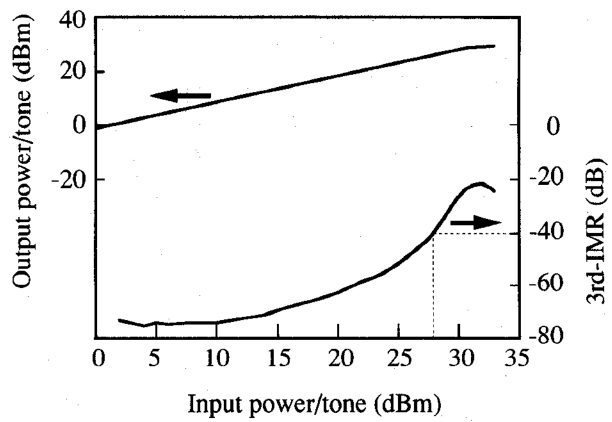
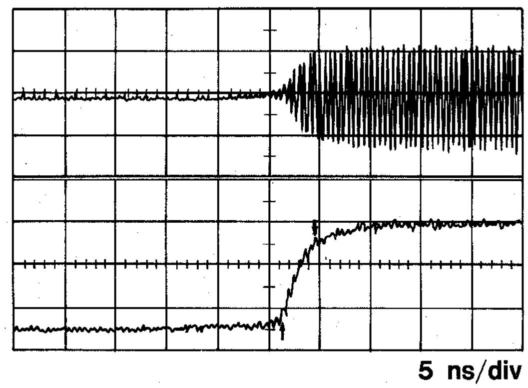
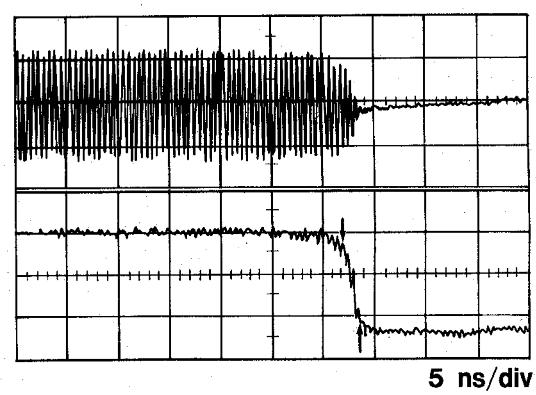


Fig. 11. Linearity of the LC-resonant T/R switch improved in power-handling capability.



(a)



(b)

Fig. 12. (a) Rise and (b) fall time characteristics of the LC-resonant T/R switch.

insertion loss for the transmit mode is reduced by 0.2 dB. The power-handling capability is 20 dB higher at the 2-V operation and 6 dB higher even at the 5-V operation when compared to that of conventional series/shunt FET T/R switches shown in Fig. 2.

C. Rise/Fall Time Characteristics

Fig. 12 shows the rise/fall time characteristics that were measured using a 100 kHz, 50% duty pulse of control voltage. The rise/fall time of the control pulse is 0.9 nsec. At −2 V/0 V control voltages, the LC-resonant T/R switch exhibits a rise time of 3.2 nsec and a fall time of 1.7 nsec. The response is equivalent that obtained with conventional T/R switches.

V. Frequency Response Improvement

Improvement of the frequency response of the LC-resonant T/R switch is addressed in this section. The insertion loss in the receive mode is 1 dB larger than that in the transmit mode, and the bandwidth for the RX arm is narrower than that of the TX arm (Figs. 8 and 9). The method used to solve this problem

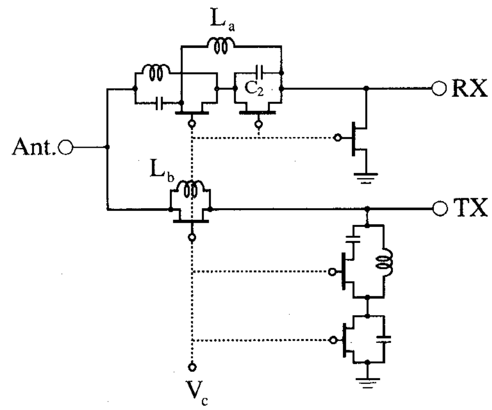


Fig. 13. An LC-resonant T/R-switch circuit scheme that introduces additional inductors in RX and TX arms to improve the RX arm characteristics.

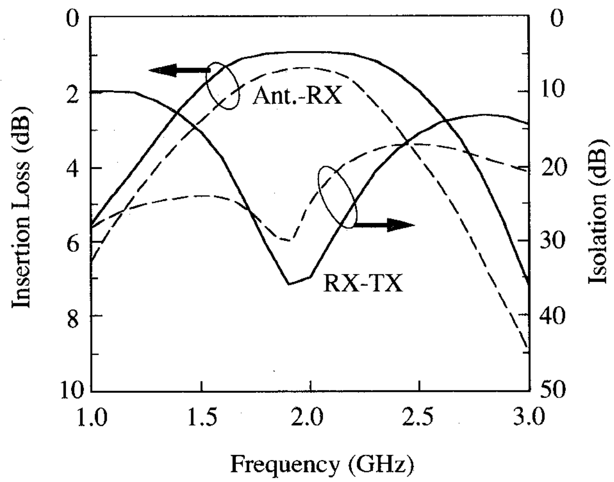


Fig. 14. RX arm frequency characteristics of the improved LC-resonant T/R switch (solid lines) and of the prototype (dashed lines).

is shown in Fig. 13, where inductances L_a and L_b are added to the T/R switch in Fig. 10. Inductor L_a doubles the signal path in the RX arm to reduce the insertion loss and the Q factor; however, it contributes only when the switch FET's are off (in the receive mode). Capacitor C_2 in the resonant circuit is redesigned as the resonant frequency remains as $(L_1C_1)^{-1/2}$. Inductor L_b cancels the stray capacitance of the series FET to enhance the total performance. Fig. 14 shows the simulated receive-mode performance, where $L_a = L_b = L_1$ and $C_2 = 0$. Performance in the other mode is very close to that shown in Fig. 8. Inductor L_a is effective in balancing the TX and RX arm in the frequency response.

VI. Conclusion

Low-voltage, high-power T/R-switch MMIC's using a novel FET-switchable LC resonator have been demonstrated. The ability of the LC-resonant T/R switch to control high levels of power with low distortion even at low levels of DC voltage makes it ideally suitable for transmit/receive switch applications in hand-held, battery-powered communications equipment. Furthermore, this ability will offer high-power switchings at millimeter-wave frequencies where breakdown voltage of active devices is low.

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Tsuneo Tokumitsu (M'88) was born in Hiroshima, Japan, in 1952. He received the B.S. and M.S. degrees in electronics engineering from Hiroshima University, Hiroshima, Japan, in 1974 and 1976, respectively.

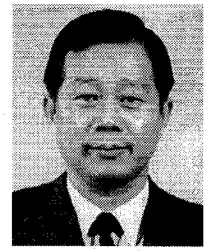
He joined the Yokosuka Electrical Communication Laboratories, Nippon Telegraph and Telephone Public Corporation (NTT), Yokosuka, Japan, in 1976. He had been involved in developmental research on microwave and millimeter-wave GaAs FET circuits and GaAs MMIC's for space applications. In September 1986, he joined ATR Optical and Radio Communications Research Laboratories, Osaka (now, Kyoto), Japan, on leave from NTT. At ATR his primary interests were in achieveing FET-sized, wide-band circuit function modules (LUFET's), multilayer MMIC's, and active inductors for highly integrated MMIC's. Since February 1990, he has been with NTT Radio Communication Systems Laboratories, Yokosuka, Japan. After he accomplished high-linearity MMIC T/R modules for 16-QAM digital radio trunk transmission systems in early 1993, he has been engaged in developmental research on novel MMIC technology including three-dimensional and advanced uniplanar MMIC's.

Mr. Tokumitsu is a recipient of the 1991 Microwave Prize granted by the IEEE Microwave Theory and Techniques Society. He is a member of the Institute of Electronics, Information and Communication Engineering of Japan.

Ichihiko Toyoda (M'91) was born in Osaka, Japan, on May 10, 1962. He received the B.E., M.E., and D.E. degrees in communication engineering from Osaka University, Osaka, Japan, in 1985, 1987 and 1990, respectively.

In 1990, he joined NTT Radio Communication Systems Laboratories, Kanagawa, Japan. His current interests are uniplaner and three-dimensional MMIC's and their applications based on electromagnetic analysis.

Dr. Toyoda was granted the 1993 Young Engineer Award by the Institute of Electronics, Information and Communication Engineering (IEICE) of Japan. He is a member of the IEICE of Japan.



Masayoshi Aikawa (M'78) was born in Saga, Japan, on Oct. 16, 1946. He received the B.S., M.S., and Dr. Eng. degrees in electronics engineering from Kyushu University, Fukuoka, Japan, in 1969, 1971, and 1985, respectively.

In 1971, he joined the Musashino Electrical Communication Laboratories, Nippon Telegraph and Telephone Public Corporation (NTT), Tokyo, Japan, where he did research and development on microwave and millimeter-wave integrated circuits, and equipment for 20-GHz digital radio trunk transmission systems and 26-GHz subscriber radio systems. In 1986, on leave from NTT, he joined ATR Optical and Radio Communication Research Laboratories, Osaka, Japan, where he was engaged in research on basic techniques such as highly integrated MMIC's and RF signal processing for future mobile communications. He is now with the NTT Radio Communication Systems Laboratories, Yokosuka, Japan, where he has been engaged in research and development on monolithic microwave and millimeter-wave integrated circuits and their applications to terrestrial, mobile, and satellite communication systems.

Dr. Aikawa is a corecipient of the 1991 Microwave Prize granted by the IEEE Microwave Theory and Techniques Society. He is a member of the Institute of Electronics, Information and Communication Engineering of Japan.