Very Small Control Modules with Line Unified FET Configuration for Array Processing

Shinji Hara, *Member, IEEE*, and Tsuneo Tokumitsu, *Member, IEEE*

***Abstract*—Very small, broad-band circuit function modules which operate as signal pass switches, phase inverters, and balanced modulators are proposed. They are realized by mutual on/off switching of the FET's in the line unified FET (LUFET) configuration [1], [2], with which a main circuit function can be realized in almost the same size as a conventional FET. It is demonstrated that a balanced modulator with a chip size of only 0.6 mm × 0.5 mm can control signal gain from 0.7 to −0.7 continuously while input and output impedances are independent of control bias and isolation is more than 35 dB up to 18 GHz. These circuit function modules are valuable in constructing miniaturized phase shifters and highly integrated circuits for array processing.**

I. Introduction

In a phased array antenna, many phase shifters are required [3], [4]. They must be very small. In a switched line phase shifter, phase shifter components include 1×2 and 2×1 signal pass switches and phase delay elements such as transmission lines or filters. In an analog phase shifter, phase shifter components include a 90° phase splitter, balanced modulators, and an in-phase combiner; other phase shifters include such components as a phase inverter and a variable attenuator [5]–[9].

As applications of the signal control components now used in phase shifters are extended further, miniaturization of these components will be vital for high-frequency signal processing in an adaptive array antenna [10] for high-speed, intelligent microwave systems. In these systems, many nonamplifier [11] circuits are required and they have to be very small. The main circuit functions required in such signal processing are multiport dividing/combining, signal pass switching, phase controlling, and level controlling.

In this paper experimental results are reported for miniature broadband MMIC control modules, operating up to *Ku*-band, which utilize the line unified FET (LUFET) configuration [1], [2]. In the LUFET configuration, coplanar lines such as slotlines and coplanar waveguides are effectively unified with the GaAs FET electrodes by regarding some sets of the GaAs FET parallel electrodes as a combination of several coplanar microwave transmission lines. The LUFET configuration obviates the necessity of using 1/4 wavelength transmission lines for either signal isolation or matching networks when active matching techniques [12] are used simultaneously. As a result, GaAs FET's as three-port microwave "devices" can, by modifying the electrode allocations and electrical relationships between the unified coplanar lines, serve as active microwave "circuit function modules." LUFET's have the following features in almost the same size as a conventional FET: (i) an ability to perform most or all fundamental circuit functions and (ii) ultra-wideband operation owing to the absence of frequency-dependent distributed lines. To extend the "LUFET family" and increase the number of applications of LUFET's, signal control modules which are realized by mutual on/off switching of the FET's in the LUFET configuration are proposed. The modules described in this paper are 1×2 or 2×1 switches, phase inverters, and balanced modulators. A combination of the balanced modulator and the other LUFET's will reduce the chip size of a 360° analog phase shifter. An advantage of a circuit design based on the LUFET over the conventional circuit design based on microstrip lines is also described. The LUFET-based modules are very useful not only for miniaturized phase shifters but also for highly integrated array processing circuits, such as those used in adaptive array antennas and microwave neural networks.

II. Switching Divider/Combiner

Fig. 1 shows a photograph of a fabricated in-phase switching divider and the equivalent circuit. In Fig. 1(b), the solid arrows and dashed arrows represent the electric field in the slotlines (SLOT) and coplanar waveguide (CPW) when FET1 is in the on state and when FET2 is in the on state, respectively. Ion-implanted FET's with a 0.5 μm gate length are used. Each FET has a 100 μm gate width. The chip size is 0.6 mm × 0.5 mm and the intrinsic part is only 0.2 mm × 0.2 mm. This module has a GaAs FET electrode allocation of drain–gate–source–gate–drain. The gate electrodes are connected through an air bridge on one side, and a coplanar waveguide is formed in the gate–source–gate structure. There are two slotlines in the drain–gate structures; these are where the slotlines and coplanar waveguide are electrically isolated from one another owing to the unilateral characteristics of the common-gate GaAs FET. This module operates as an in-phase divider LUFET when both FET's are in the on state [1]. When FET1 at port ② is in the on state and FET2 at port ③ is in the off state, the input signal from port ① appears only at port ②. Conversely, when FET1 at port ② is in the off state and FET2 at port ③ is in the on state, the input signal from port ① appears only at port ③. The input impedance is approximately equal to the reciprocal of each GaAs FET transconductance, g_m, up to

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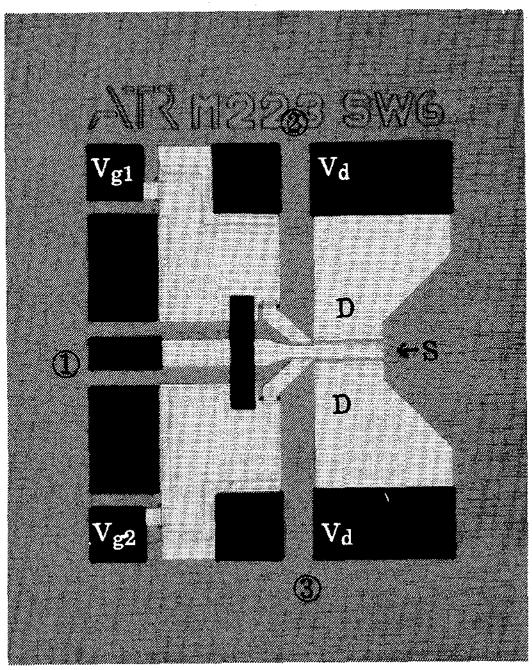

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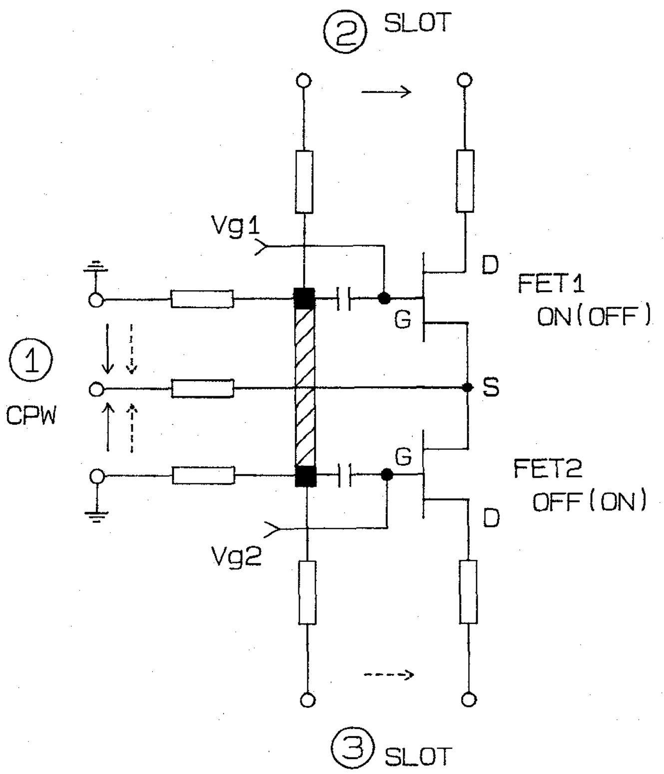

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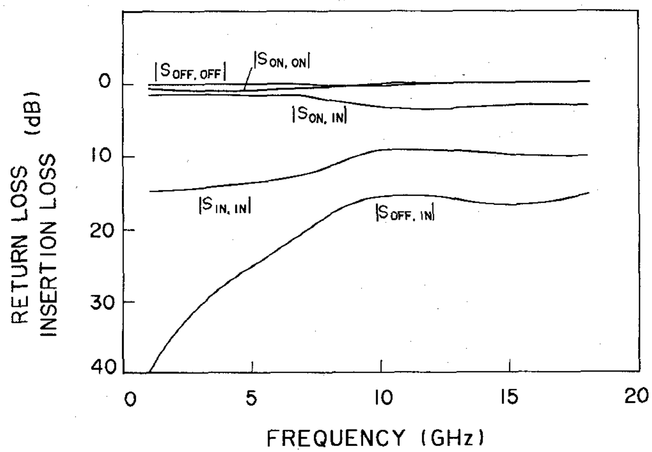
Fig. 1. The schematics of a fabricated in-phase switching divider. (a) Photograph of the chip. (b) Equivalent circuit (▩ indicates the air bridge).



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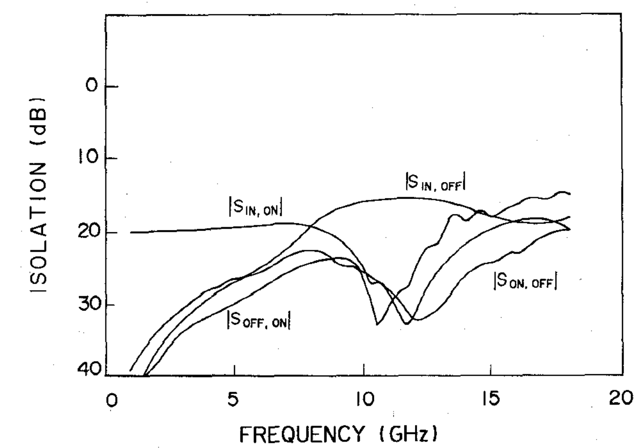

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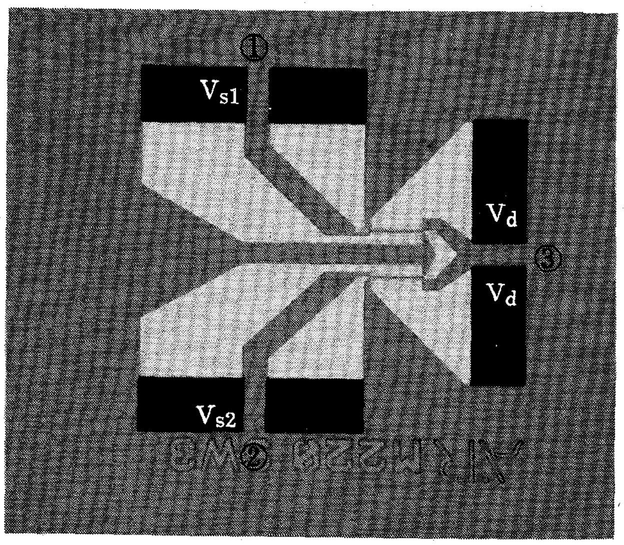
Fig. 2. Measured performance of in-phase switching divider. (a) Return and insertion loss. (b) Isolation.

frequencies approaching the GaAs FET cutoff frequency, f_t. There are also ultra-wide-band isolation characteristics from each output port to the input port, as well as between the two output ports, because of the unilateral characteristics of the common-gate GaAs FET's. Therefore, this LUFET has the following functions in FET size: signal pass switching, input–output isolation, output–output isolation, and input impedance matching.

Fig. 2 shows the measured performance of the in-phase switching divider. In the figure, the subscripts "on," "off," and "in" represent, respectively, the output port which is in the on state, the output port which is in the off state, and the input port. Port ②, when FET1 is in the on state, is the equivalent of port ③ when FET2 is in the on state, because the two output ports are symmetrical in the chip pattern. The on–off ratio is not good in the high-frequency range but isolation between the ports and input matching are realized in a very wide frequency range. The port isolation is more than 15 dB, insertion loss is almost 2 dB, on/off ratio is more than 15 dB, and return loss is more than 9 dB up to 18 GHz. With regard to the return loss, the fabricated module has a g_m of almost 10 mS. If 200-μm-gate-width FET's are used, the return loss of the input port increases.

Fig. 3 shows a photograph of a fabricated out-of-phase switching combiner and the equivalent circuit. In Fig. 3(b), the solid arrows and dashed arrows represent the electric field in the slotlines (SLOT) when FET1 is in the on state and when FET2 is in the on state, respectively. Each FET has a 100 μm gate width. The chip size is 0.75 mm $\times$ 0.7 mm. This module has two FET's, which have an electrode allocation of drain–gate–source (FET1) and source–gate–drain (FET2), where the gates are connected to each other. The



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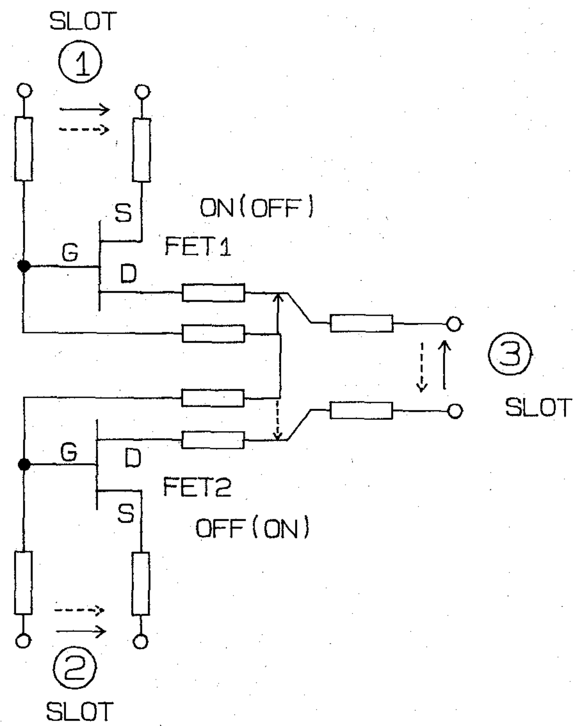

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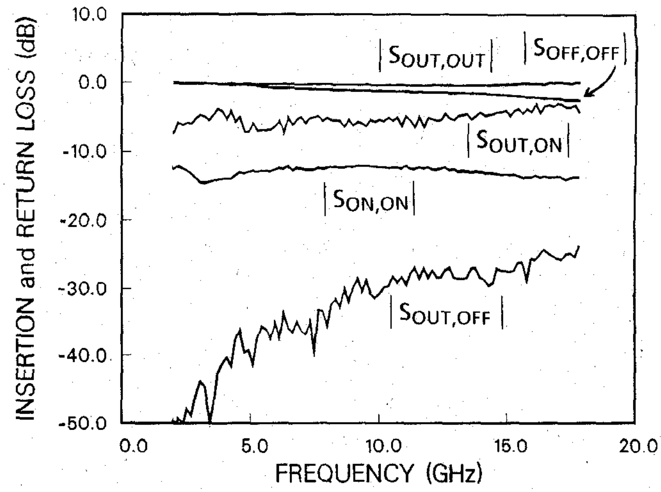
Fig. 3. The schematics of a fabricated out-of-phase switching combiner. (a) Photograph of the chip, (b) Equivalent circuit.



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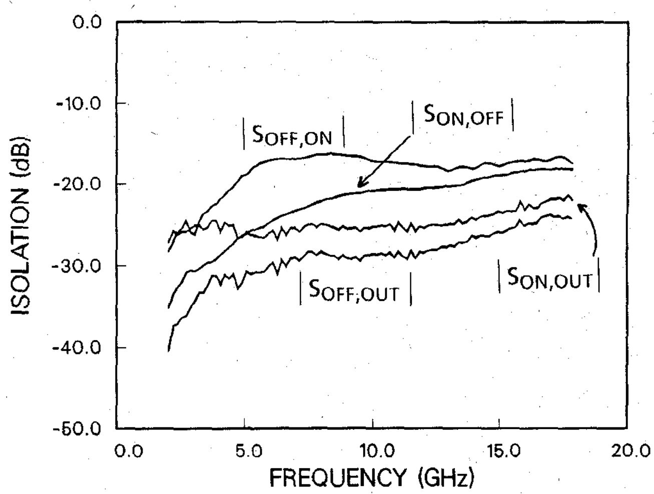
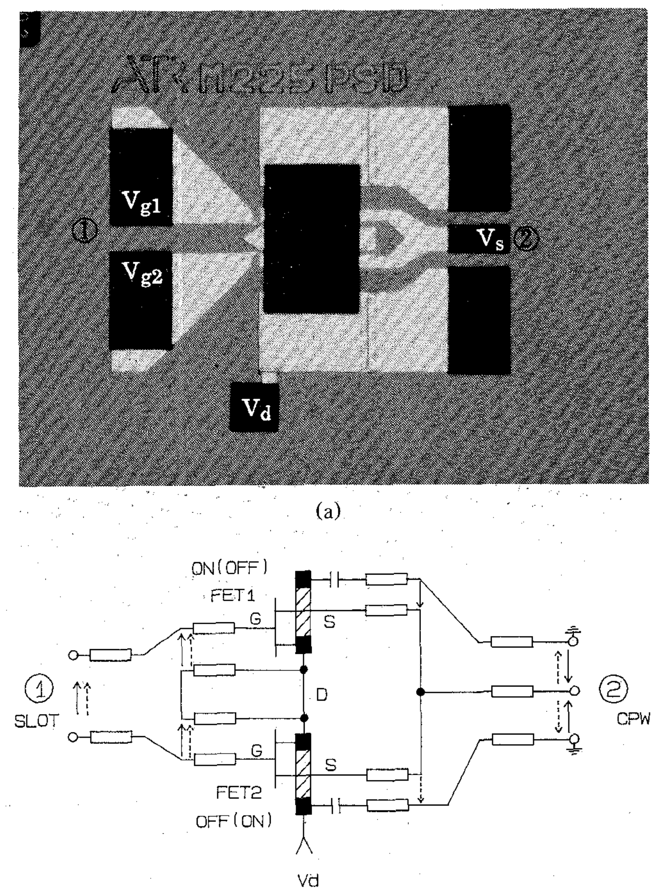


Fig. 4. Measured performance of out-of-phase switching combiner. (a) Return and insertion loss. (b) Isolation.

source–gate structures form slotlines which are the two input ports on the left side of the chip, as shown in Fig. 3. At the right side of the figure, a slotline series T junction as an out-of-phase combiner is formed with a conductive pad connecting the two gate electrodes and two drain electrodes, one on each side of the pad. This module operates as an out-of-phase combiner LUFET when both FET's are in the on state [2]. When FET1 at port ① is in the on state and FET2 at port ② is in the off state, only the input signal from port ① appears at output port ③. Conversely, when FET1 is in the off state and FET2 is in the on state, only the signal from port ② appears at output port ③. There are also ultra-wide-band isolation characteristics from the output port to each input port, as well as between two input ports, because of the unilateral characteristics of the common-gate GaAs FET's.

Fig. 4 shows the measured performance of the out-of-phase switching combiner. In this figure, the subscripts "on," "off," and "out" mean, respectively, the input port which is in the on state, the input port which is in the off state, and the output port. Port ①, when FET1 is in the on state, is the equivalent of port ② when FET2 is in the on state, because two input ports are symmetrical in the chip pattern. The isolation between the ports is more than 16 dB, the insertion loss is almost 5 dB, and the on–off ratio is more than 20 dB up to 18 GHz. With regard to the return loss, this module has the common-gate configuration. The input matching is, therefore, obtained at the port with the on state FET.

There are many variations in switching dividers/combiners, because these modules are obtained by mutual on/off operation of divider/combiner LUFET's [1], [2]. Using these modules in a switched line phase shifter will result in a size reduction. Broad-band impedance matching is easily obtained, particularly when an in-phase switching divider with



(a)

(b)

Fig. 5. The schematics of a fabricated phase inverter. (a) Photograph of the chip. (b) Equivalent circuit (▨ indicates the air bridge).

the common-gate configuration and an in-phase switching combiner with the common-drain configuration are used. A $C-R$ filter can be used as a phase delay element because the impedance between the divider and the combiner is high, although it has a loss.

Furthermore, by using dual-gate FET's instead of single-gate FET's in the common-source configuration, the modules can operate as weighting combiners or dividers. Such modules would be very useful for signal processing, for example in an adaptive array antenna.

III. Phase Inverter

Phase inverters are realized by the in-phase combining of the output ports of out-of-phase divider LUFET's or the input ports of out-of-phase combiner LUFET's. Fig. 5 shows a photograph of a fabricated phase inverter and the equivalent circuit. Each FET has a 200 μm gate width. In Fig. 5(b), the solid arrows and dashed arrows represent the electric field in the slotlines (SLOT) and the coplanar waveguide (CPW) when FET1 is in the on state and when FET2 is in the on state, respectively. The chip size is 0.7 mm$\times$0.5 mm. This pattern is constructed by combining two source electrodes of two output slotlines of an out-of-phase divider LUFET as the center conductor of the coplanar waveguide. This module has a GaAs FET electrode allocation of source–gate–drain–gate–source. A slotline series T junction

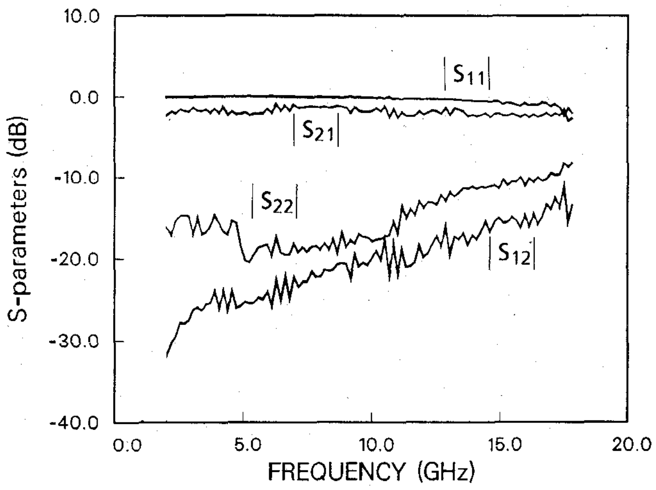
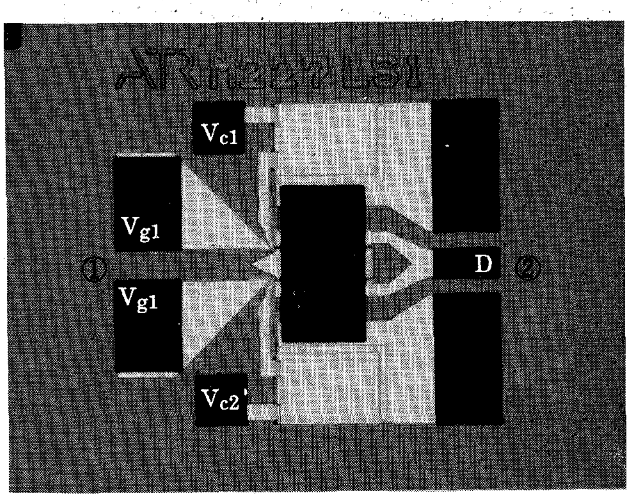


Fig. 6. Measured performance of phase inverter.

as an out-of-phase power divider is formed in the gate–drain–gate structure. The common-drain electrode is connected to the outer conductor of the coplanar waveguide by an air bridge. The input signal from port ① is divided out of phase by the slotline series T junction formed by the gate–drain–gate electrode and an antiphase signal is input at each FET. When both FET's are in the on state, the signal does not appear at output port ② because the out-of-phase signals, one from each FET, are combined in phase. When one FET is in the off state, the signal comes only from the other FET and a signal is output. Conversely, the out-of-phase signal is output. This is because the two signals which input each FET are out of phase and the pattern is symmetrical. Furthermore, this module has output matching characteristics owing to the common-drain configuration. Fig. 6 shows the measured performance of this phase inverter. The insertion loss is 2 dB, the isolation is more than 15 dB, and the output return loss is more than 10 dB up to 17 GHz. This module will be used as, for example, a 180° phase shifter and a component of a phase shift keying modulator.

IV. Balanced Modulator

By using dual-gate FET's instead of single FET's in the phase inverter, the module can operate as a balanced modulator. Fig. 7 shows a photograph of a chip and the equivalent circuit of one example of a balanced modulator. The chip size is only 0.6 mm$\times$0.5 mm. The gate width of each FET is 150 μm. This module has a configuration identical with that in Fig. 5, except that it uses dual-gate FET's in the common-source configuration. This module has a GaAs FET electrode allocation of drain–gates–source–gates–drain. Two first gates and the source electrode form a slotline series T junction as an out-of-phase divider. The source electrode is connected to the outer conductor of the coplanar waveguide by an air bridge. The two drains are connected at the inner electrode of the coplanar waveguide. Each second gate is used to control the output signal level. The output from each FET is at some level P_o to 0 and is controlled by the second gate voltage. The two outputs are out of phase with each other, because the input signal is divided out of phase by the slotline T junction and fed to each gate–source. Therefore,



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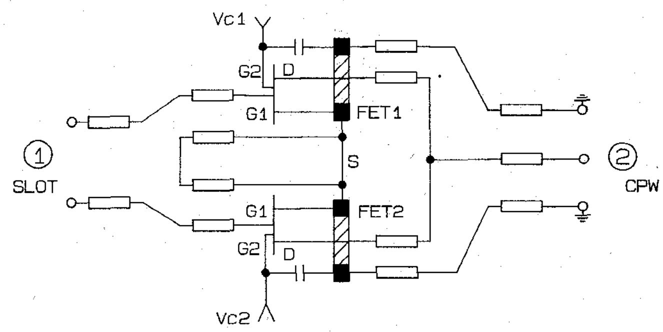

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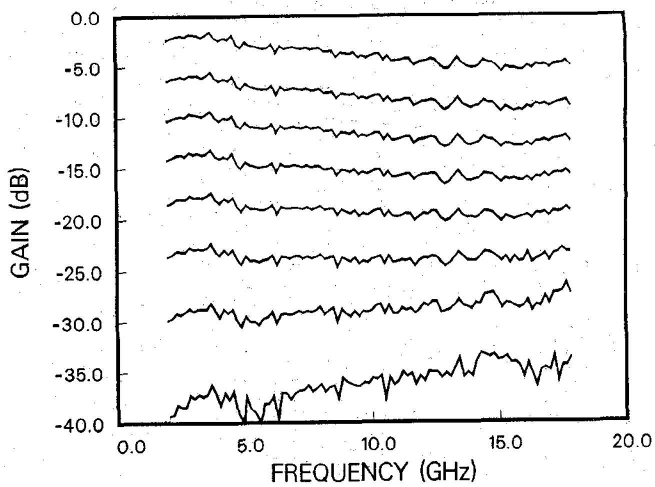
Fig. 7. Schematics of a fabricated balanced modulator. (a) Photograph of the chip. (b) Equivalent circuit ([air bridge symbol] denotes the air bridge).



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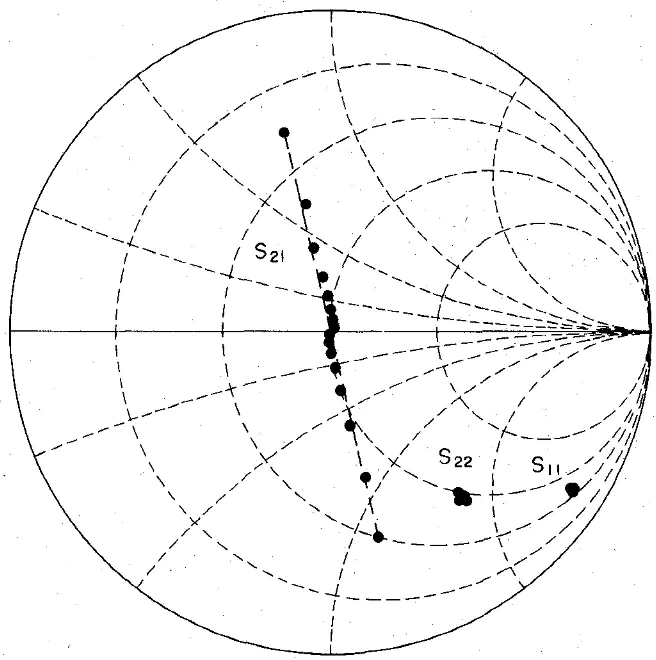


(b)

Fig. 8. Measured performance of balanced modulator. (a) Frequency characteristics of voltage control gain. (b) Gain and impedance characteristics versus control voltage at 10 GHz.

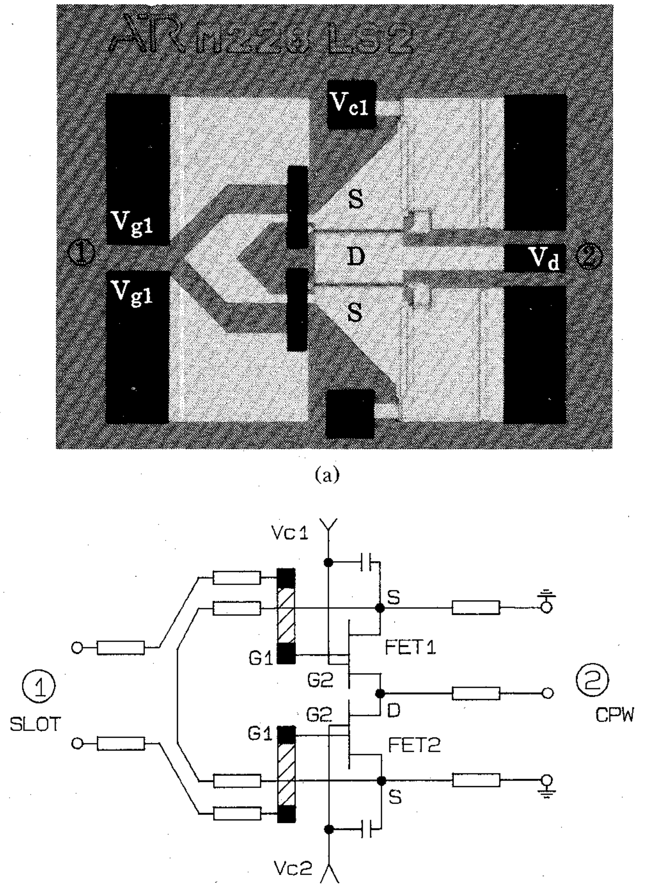
the output signal can be continuously controlled from P_o to $-P_o$.

Fig. 8 shows the measured performance of this module. Fig. 8(a) shows the variable gain characteristics. One second gate bias is changed while the other second gate bias is in the off state. Variable gain performance is obtained over a very broad band. Fig. 8(b) shows how the gain and impedances are changed by the second gate bias voltages at 10 GHz. The gain S_{21} is controlled from 0.66 to -0.66, while the input and output impedances do not change. Isolation S_{12} is more than 35 dB over all frequency points and at any bias point.

Fig. 9 shows a photograph of a chip and the equivalent circuit of another example of a balanced modulator. The chip size is 0.8 mm$\times$0.6 mm. The gate width of each FET is 150 μm. This module has a GaAs FET electrode allocation of source–gates–drain–gates–source. A slotline T junction as an out-of-phase divider is formed with a conductive pad connecting the two source electrodes and two first gates. Two source electrodes which have the same potential by the conductive pad at the input port, and a drain construct the coplanar waveguide at the output port. The equivalent circuit of this module is same as that shown in Fig. 7(b). As with the module shown in Fig. 7, the output signal can be controlled from P_o to $-P_o$ continuously by the second gate voltages.

Fig. 10 shows the measured performance of this module. Fig. 10(a) shows the variable gain characteristics of the output level. One second gate bias is changed while the other second gate bias is in the off state. As with the former module shown in Fig. 7, very broad band and flat gain control are realized in a very small size. Fig. 10(b) shows how the gain and impedances are changed by the second gate bias voltages at 10 GHz. Gain S_{21} is controlled from 0.7 to -0.7, while the input and output impedances do not change. Isolation S_{12} is more than 35 dB over all frequency points and at any bias point.

Because these modules are very small and broad band, they are effectively used in a 360° continuous phase shifter as shown in Fig. 11. Conventionally, this type of phase shifter is composed of a 90° hybrid, two balanced modulators, and an in-phase hybrid. Conventional hybrids based on passive transmission lines are very large in MMIC's because they need several 1/4 wavelength lines. Furthermore, it is very difficult to make a small balanced modulator in a conven-



(a)

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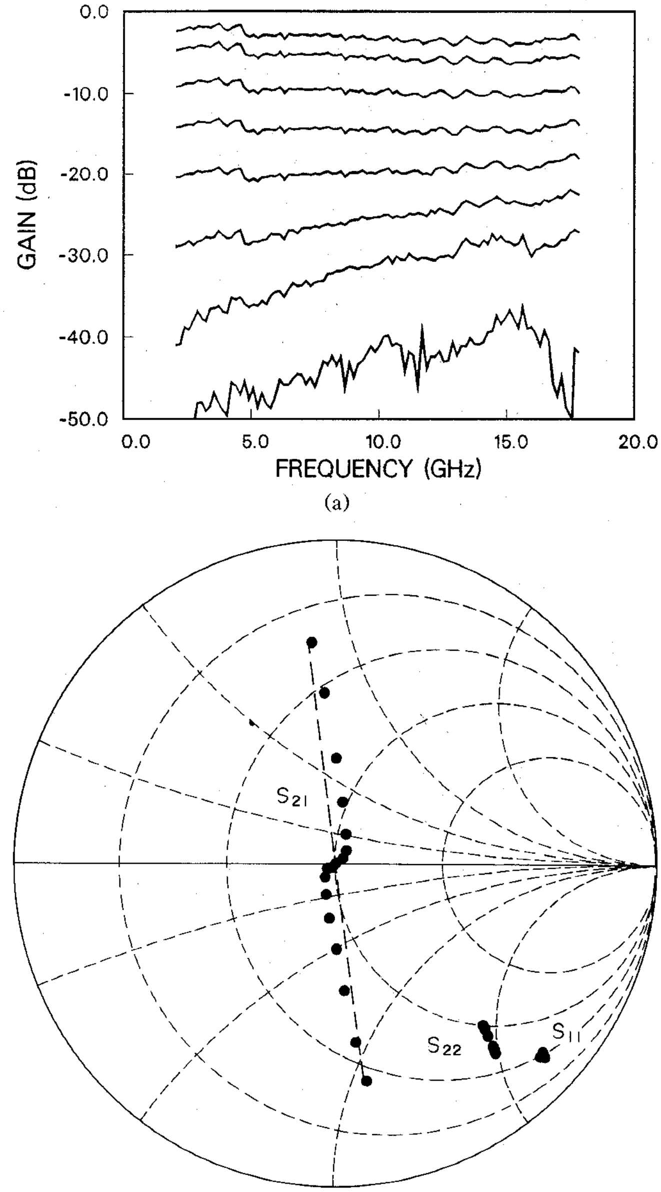
Fig. 9. Schematics of a fabricated balanced modulator. (a) Photograph of the chip. (b) Equivalent circuit (▮▨▮ indicates the air bridge).

tional microstrip type MMIC [16]. Such a modulator might, for example, be composed of an in-phase divider such as a Wilkinson divider, two variable amplifiers, and a 180° hybrid such as the rat-race type. Therefore, a conventional 360° continuous phase shifter needs many components, and cannot be small or simply configured. In the balanced modulator module, slotlines and coplanar waveguides are effectively unified with the electrode allocation of the FET. Therefore, very broad band operation is realized in a very small size and a simple configuration. The impedance of the balanced modulator is high. Therefore, a combiner LUFET with a CDF configuration [2] will be used as a signal combiner. With regard to a 90° phase splitter, a circuit in which $C-R$ high-pass and $R-C$ low-pass filters are attached to two output ports of the CGF divider LUFET [2] will be used because the output impedance of the CGF and the input impedance of the balanced modulator module are both high, although theoretically it has a 3 dB loss. A branch line hybrid using thin film microstrip lines (TFM's) [17] can be also used as a 90° phase splitter over X-band to reduce the chip size.

In Table I, the circuit elements which are used in a phase shifter are summarized. The new circuit based on the LUFET is very small compared with a conventional circuit based on microstrip lines. Furthermore, if a miniaturized 90° phase divider module is realized, then a very small continuous phase shifter can also be realized by the modular design approach [18].



(a)

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Fig. 10. Measured performance of balanced modulator: (a) frequency characteristics of voltage control gain; (b) gain and impedance characteristics versus control voltage at 10 GHz.

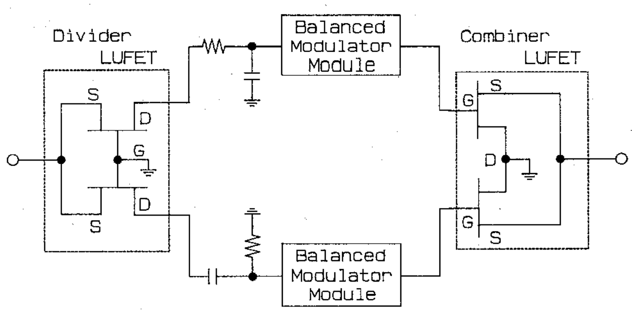

Fig. 11. Block diagram of 360° continuous phase shifter using LUFET's and the balanced modulator modules.

TABLE I
EXAMPLE OF MICROWAVE ELEMENTS USED IN A PHASE SHIFTER

	Conventional Circuit Based on Microstrip Lines	New Circuit Based on FET Oriented Modules
90° Divider	Branch-Line Hybrid	In-Phase Divider LUFET(CGF) and *R–C* Filters
Balanced	Wilkinson Divider, Variable Amplifier, and Rat-Race Hybrid	Balanced Modulator Module
In-Phase Combiner	Wilinson Combiner	In-Phase Combiner LUFET(CDF)

V. CONCLUSION

Very small, broad-band circuit function modules are proposed and realized by using the idea of line unified FET's (LUFET's). They have functions such as signal pass switching, phase controlling, and level controlling up to *Ku*-band and have a chip size almost equal to that of conventional FET's. These new modules should prove valuable in realizing a miniaturized phase shifter and highly integrated signal processing circuit for an adaptive antenna.

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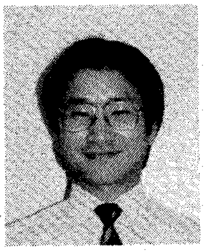

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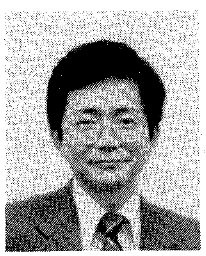

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