Control of Mode-Switching in an Active Antenna Using MESFET

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***Abstract*—New techniques of realizing mode-switching in an active antenna by using MESFET are presented. Two types of control circuits are discussed. One is the control circuit using the reactance variation of MESFET and the other is the control circuit using the resistance variation of MESFET. The design of these two control circuits is discussed and the beam-switching phenomena of the antenna using these control circuits are compared. Important characteristics such as antenna patterns, operating frequencies and the insertion loss of the control circuits are also compared and discussed.**

I. INTRODUCTION

THE ACTIVE antenna becomes a promising candidate in the growing world of microwave and millimeter-wave communications with advantages of low profile, light weight, easy fabrication and suitability of mass production. In order to achieve solid-state high power sources at millimeter region, effort of combining power using active antenna arrays has been made as one of the quasi-optical power combining technologies [1]–[5]. Among these array type of combiners, strongly coupled arrays [6], [7] have drawn attention because of simplicity of the circuit configuration which is important in MMIC technology. Although the multimoding effect is a problem associated with strongly coupled arrays [8], it is possible to select appropriate modes. For instance, beam-switching between sum and difference patterns is considered useful since the two different patterns can be used for different purposes such as communications and tracking objects.

The mode-switching phenomenon of two different oscillation modes of a strongly coupled active antenna has already been verified theoretically and experimentally [9]. This phenomenon was explained by the analysis based on the averaged potential theory and the nonlinear device model. An electromagnetic simulation using the FDTD method was applied to this circuit and confirmed this mode-switching phenomenon [10]. In this circuit, a chip resistor was used to stabilize the in-phase oscillation mode and to radiate the sum pattern while a metal strip was used to support the anti-phase oscillation mode and to radiate the difference pattern. Appropriate external devices were proposed for electronic switching of the oscillation modes as well as the radiation patterns.

Meanwhile, control of the microwave circuit using MESFET has been an area of growing interest [11]–[13]. Particularly, the optical control of the MESFET is considered useful if the physical area of a circuit becomes small and the electromagnetic immunity becomes important [14], [15]. Photoconductive and photovoltaic effects are considered important for optical control. These effects induce the resistance and capacitance variation of MESFET respectively. In this paper, the use of the capacitance variation in a reactive FET circuit, which has been used for electronic and optical control in various circuits as a tuning element [11], [12], is investigated experimentally for controlling the radiation patterns of an active antenna. Also, another new technique of using the resistance variation of MESFET is investigated experimentally for the same switching purpose. The design and the experimental results of both circuits using reactive FET and resistance variation of MESFET are discussed and compared.

II. DESIGN

Both the variation of gate-to-source capacitance C_{gs} and drain-to-source resistance R_{ds} of MESFET used as a control element are examined in a two-element active array antenna. The MESFET used here is a package type NE72084 (NEC). The unit active antenna constructing the array has the same structure in both cases. Each single antenna unit consists of a packaged Gunn diode as the active device and a microstrip patch antenna as the radiator. The active array antenna was fabricated using Duroid 5870 with a thickness of 31 mils and a dielectric constant of 2.33. The patch antennas were designed to have the same resonant frequency of 12.45 GHz. Each single active antenna is designed at 12.45 GHz based on the measurement of large signal impedance of Gunn diode [5]. Detailed design procedure of single active antenna is the same as that in [16].

A two-element active antenna used here is constructed by connecting the two unit active antennas with the coupling line whose length is equal to one guided wavelength at 12.45 GHz

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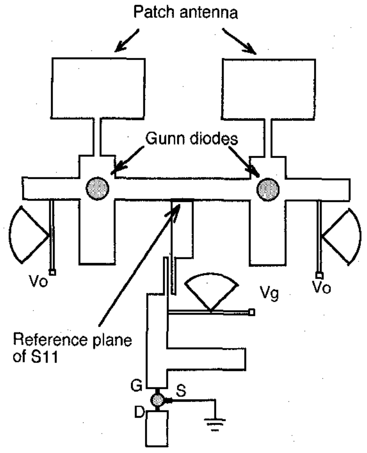


Fig. 1. Configuration of the active antenna with reactive FET circuit connected to the coupling line in shunt.

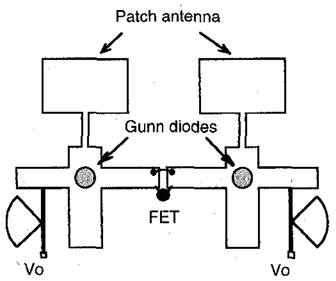


Fig. 2. Configuration of the active antenna with FET connected across the coupling line gap in series.

as shown in Figs. 1 and 2, which include control circuits as well using C_{gs} and R_{ds} respectively. In order for the active antenna to radiate a sum pattern and a difference pattern, both oscillators must have in-phase and anti-phase oscillation modes respectively. Since the in-phase and anti-phase oscillation modes have open and short boundaries at the center of the coupling line respectively [9], it is expected that the antenna pattern switching between sum and difference patterns could be achieved by the boundary condition switching between open and short boundaries at the center of the coupling line. Prior to the introduction of an extra control circuit for the switching, the active antenna without control circuits is designed to oscillate at the in-phase mode of 12.45 GHz. The design procedure is similar to that in [9] except that the stable mode is the in-phase mode while the stable mode in [9] was the anti-phase mode.

Two types of control circuit are considered. One type is a shunt connection of the control circuit to the coupling line of a strongly coupled active antenna. This circuit controls the current indirectly by impedance control which induces the change of boundary conditions on the coupling line [17]. The other type is a series connection of the control circuit placed across the gap on the center of the coupling line, which controls the current [18]. In this paper, the C_{gs} variation of the MESFET is examined in the control circuit connected in shunt as shown in Fig. 1 to change the boundary conditions. Also, the R_{ds} variation of the MESFET is examined in the control circuit connected in series to control the current as shown in Fig. 2.

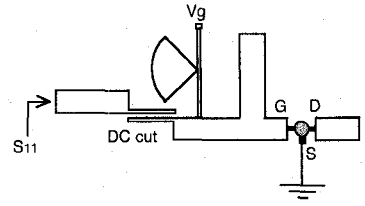
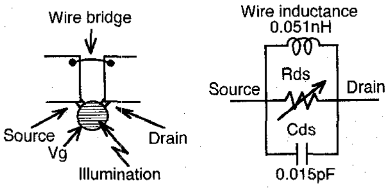


Fig. 3. Configuration of the reactive FET circuit.



(a) (b)

Fig. 4. Control circuit connected to the coupling line in series: (a) Physical layout. (b) Equivalent circuit model.

In the case of the reactance control circuit, the input port of the control circuit called reactive FET in Fig. 3 is attached to the center of the coupling line as shown in Fig. 1. By changing the bias voltage of the MESFET, the S_{11} of the input port of the reactive FET can be varied due to the variation of the reactance provided by the MESFET. The variation of S_{11} is expected to change the boundary condition at the center of the coupling line and induces a change in mode stability and thus changes the oscillation mode as well as the radiation pattern. Only the gate-to-source bias V_g of the MESFET in Fig. 3 is used as a control terminal to realize a large reactance variation. The drain-to-source bias is floated for simplicity of the structure.

On the other hand, in the case of the resistance control circuit, the coupling line has a gap at its center, which is connected by a MESFET and a wire bridge as Fig. 4 shows. In this case, the current on the center of the coupling line is controlled by the variation of R_{ds} to switch the oscillation modes. In order for the antenna to radiate a sum pattern, a low current is necessary at the center of the coupling line, which corresponds to the open boundary. On the other hand, for a difference pattern, a high current is necessary at the center of the coupling line, which corresponds to the short boundary. The cover of the FET is removed to receive optical illumination. The effect of removing the cover is found negligible. A halogen lamp fiber illuminator is used as the optical source. In order to use the variation in Rds, drain and source terminals are connected to the coupling line. V_g or external light source is used to control the circuit. The variation of R_{ds} induced either by the control of V_g or by the optical illumination controls the current at the center of the coupling line and realizes a change in mode stability. The oscillation mode and the radiation pattern are therefore controlled electronically and optically. The effect of drain-to-source capacitance is negligible because of its small value. DC cut is not necessary in this configuration.

III. EXPERIMENTAL RESULTS

A. Active Antenna Using a Reactive Element in Shunt Control Circuit

When the reactive FET was not connected to the coupling line in Fig. 1, the active antenna initially radiated the sum pattern which came from in-phase oscillation mode. It was observed that the effective radiated power (ERP) was 14.0 dBm. The optimum reactance for the switching between the in-phase mode and the anti-phase mode is pre-determined experimentally by replacing the reactive FET with an open stub. The sum pattern is always observed for any length of the stub except when the stub length is equal to a quarter guided wavelength which supports the difference pattern. The open stub of a quarter guided wavelength has a measured S_{11} of $0.86\angle 165^\circ$ which corresponds to an almost short-circuit boundary condition at its input port. This supports the anti-phase mode and difference pattern. The reactive FET is designed to have its reactance variation range covering this optimum reactance at 12.45 GHz. The measured S_{11} of the designed reactive FET varied from $0.80\angle 92^\circ$ to $0.68\angle 176^\circ$ when V_g changed from 0—-2.0 V.

Fig. 5 shows the measured H-plane pattern of the active antenna in Fig. 1. When the bias voltage of the Gunn devices was $V_o = 7.1$ V and the reactive FET bias was $V_g = 0$ V, the sum pattern was initially obtained at 12.44 GHz as the solid line in Fig. 5 shows. When V_g was decreased to less than -1.8 V, the radiation pattern changed from the sum pattern to the difference pattern and the frequency decreased slightly to 12.39 GHz as the dotted line in Fig. 5 shows. However, the reverse switching, i. e., from difference pattern to sum pattern, was not achieved when V_g was increased to 0 V. When the bias voltage of Gunn devices was $V_o = 8.1$ V and $V_g = 0$ V, the difference pattern was initially obtained at 12.35 GHz as the solid line in Fig. 6 shows. When V_g was decreased to less than -1.7 V, the pattern changed from the difference pattern to sum pattern and the frequency decreased slightly to 12.33 GHz as the dotted line in Fig. 6 shows. The experimental results show that one-way electronic mode switching can be obtained by using V_g control. In both cases above, the radiation patterns were very distinct and the operation was stable with the slight change of the operating frequency. The patterns were normalized to the peak radiation power of the sum pattern respectively. The optical control was not available since the dynamic range of its reactance variation was smaller than the V_g control case. Also, the insertion loss of the reactive FET was within 1.7 dB for both of sum pattern and difference pattern. Two-way mode switching was observed by controlling the bias voltage of Gunn devices V_o only under $V_g = 0$ V.

B. Active Antenna Using a Resistive Element in Series Control Circuit

Fig. 7 shows the experimental result of R_{ds} in MESFET of Fig. 4 as a function of V_g and optical illumination. When $V_g = 0, R_{ds}$ is equal to 5.1 Ω under optical illumination and equal to 5.7 Ω without optical illumination. R_{ds} increases as V_g decreases. Since the resistance values between 2.0 and 4.7 Ω are considered useful for the mode-switching [16], a wire bridge is connected in pararellel with the R_{ds} as shown in Fig. 4 to decrease the total impedance of the control circuit. Fig. 8 shows the calculated result of the total impedance including Rds, the wire bridge and Cds, which covers from 3.16–4.02 Ω when the V_g changes from 0—-3.0 V. Thus the variation of R_{ds} with the help of the wire bridge can be expected to induce the mode-switching between in-phase and anti-phase.

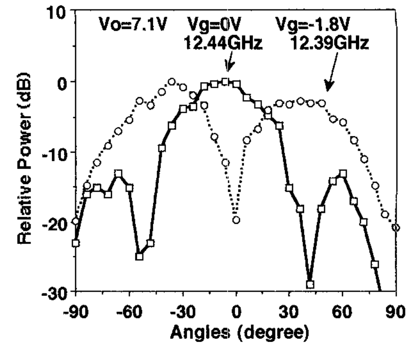


Fig. 5. Measured H-plane pattern switched from sum to difference pattern by using V_g control of reactive FET.

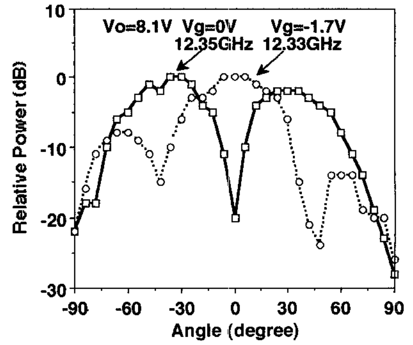


Fig. 6. Measured H-plane pattern switched from difference to sum pattern by using V_g control of reactive FET.

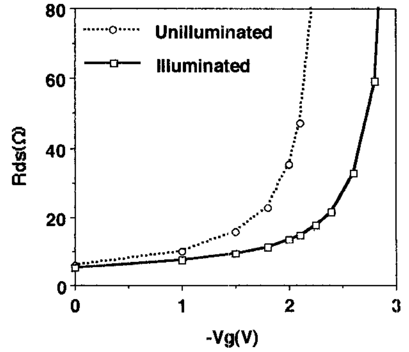


Fig. 7. Drain-to-source resistance of MESFET.

Fig. 9 shows the switching of H-plane pattern by V_g control of the active antenna in Fig. 2. Bias voltage of the Gunn diode oscillator V_o was kept constant at 7.95 V. Two-way switching between sum and difference patterns was realized by using

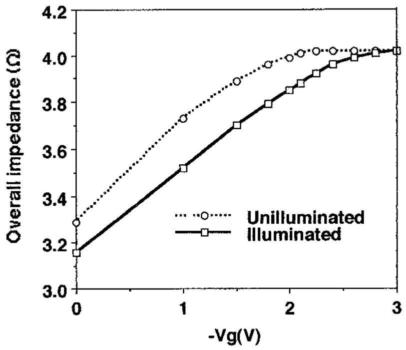


Fig. 8. Total impedance of the control circuit of Fig. 4.

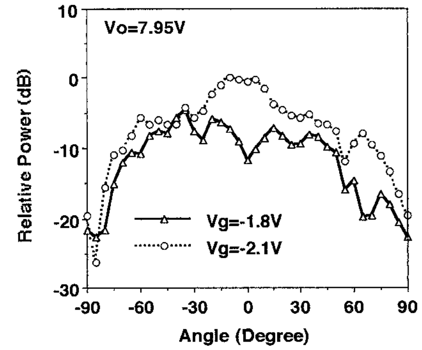


Fig. 9. Experimental result of voltage-controlled H-plane pattern by using R_{ds} control circuit.

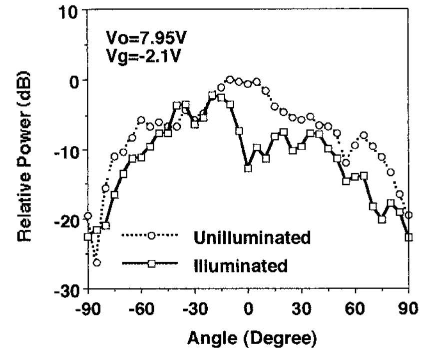


Fig. 10. Experimental result of optically controlled H-plane pattern by using R_{ds} control circuit.

V_g control of MESFET. As the solid line in Fig. 9 shows, difference pattern of 12.57 GHz was obtained at $V_g = -1.8$ V or larger. As the dotted line in Fig. 9 shows, the sum pattern of 12.47 GHz was obtained at $V_g = -2.1$ V or less. The two oscillators were not locked when V_g was between -1.8 and -2.1 V. In addition to the two-way electronic switching, two-way switching phenomenon due to optical illumination was realized. During the optical control, V_o was kept constant at 7.95 V and V_g was also kept constant at -2.1 V. As the dotted line in Fig. 10 shows, sum pattern of 12.47 GHz was observed when there was no optical illumination, which is identical to the case of V_g control at $V_g = -2.1$ V. As the solid line in Fig. 10 shows, a difference pattern of 12.55 GHz was observed when there was optical illumination. For both cases of V_g control and optical control, the total impedance of the control circuit was equal to or larger than 4.01 Ω when the sum pattern appeared as Fig. 8 shows, since the measured impedance of the wire bridge was about $j4\,\Omega$, the impedance due to C_{ds} was $-j852\Omega$ and $R_{ds} \geq 47.2\,\Omega$ when $V_g \leq -2.1$ V as Fig. 7 shows. On the other hand, the total impedance of the control circuit was equal to or less than 3.96 Ω when the difference pattern appeared as Fig. 8 shows for both cases of V_g control and optical control, since $R_{ds} \leq 22.9\,\Omega$ when $V_g \geq -1.8$ V as Fig. 7 shows. These facts agree with the results in [16] which shows the resistor of 4.7 Ω were able to stabilize the in-phase mode while the resistor of 2 Ω were not. Detailed investigation should be followed since other parasitic parameters such as lead inductance of the MESFET may have some effects. In both cases above, the switching operations were stable with the slight difference of the operating frequency between sum and difference patterns. The patterns were normalized to the peak radiation power of the sum pattern respectively. The insertion loss of the control circuit for the sum pattern was 0.6 dB while the one for the difference pattern was 5.3 dB. Furthermore, the presence of the fiber illuminator in front of the MESFET was not negligible. It has effect on the radiation patterns.

IV. DISCUSSIONS

One-way electronic beam-switching was obtained by controlling the gate-to-source bias V_g of the reactive FET while the two-way electronic switching was avilable by controllig the bias voltage V_o of the Gunn devices. The reason why only one-way switching is achieved by using the reactive FET may come from the following reason. According to the averaged potential theory and nonlinear device model [9], the lowest averaged potential (AP) corresponds to the operating mode and frequency. The AP depends on the circuit impedance and device conductance. It is assumed that the active antenna with the reactive FET has two valleys and a potential wall between the two valleys of the AP with respect to frequency around 12 GHz. Because of the unsymmetry in terms of frequncy, one-way switching could occur when the impedance change of the control circuit is small. The frequncy change with V_g of the reactive FET was very small except at the moment of the mode-switching when the slight frequency change was observed. It implies that the impedance change with V_g can be considered small, which causes the one-way switching. Meanwhile, the AP is considered to have changed well with V_o since the frequency change with V_o is larger than with V_g, which results in the two-way switching. Similarly, the two-way electronic or optical beam-switching were obtained by controlling the gate-to-source bias V_g or optical illumination of MESFET connected in series across the coupling line gap. The frequency change with V_g or optical illumination was also larger than the case of the reactive FET. Therefore, the AP variation with V_g or optical illumination is considered large enough to cause the two-way electronic or optical control.

The antenna pattern of the circuit using reactive FET was clearer than the one using the resistance variation of MESFET.

This comes from the fact that the fiber illuminator was set in front of the circuit for the case of resistance variation circuit while the illuminator was not placed for the case of reactive FET circuit. As Figs. 9 and 10 show, the effect of the fiber illuminator was considerable at peak pattern around ±30° of difference patterns. In the cases above, slight operating frequency differences were observed between sum and difference patterns while the switching operations were stable. Since V_o was kept constant and the operating frequency did not change much during the switching operations, the averaged potential of the circuit is a function mainly of the circuit impedance if we assume the RF output power did not change much. Thus the stable mode is determined mainly by the variation of circuit impedance. In our case, the switching operations were stable since this variation induced by V_g or optical illumination was very large because of the large change of boundary conditions on the center of the coupling line.

The insertion losses of the control circuit were within 1.7 dB except for the case of the difference pattern of the control circuit using resistance variation of the MESFET which had 5.3 dB of insertion loss. This fact implies that the insertion loss of the reactive FET was smaller than that of the control circuit using resistance variation of the MESFET. The advantage of using the control circuit connected in parallel such as the reactive FET investigated in this paper is that it may not dissipate the energy if an ideal lossless reactive circuit is available since the current on the coupling line is controlled indirectly as a result of impedance change due to a reactive element. On the other hand, the energy in the resistance control circuit is considered dissipated more than the case of reactive control circuit since the current is controlled by the resistance. Further, the insertion loss of resistive control circuit for the sum pattern was smaller than for the difference pattern. It is considered that the in-phase mode producing the sum pattern has small current at the center of the coupling line causing the small energy dissipation while the anti-phase mode producing difference pattern has higher current at the center of the coupling line and the energy dissipation at R_{ds} is anticipated.

There was another series-connection type control circuit. For example, the C_{gs} variation of MESFET placed across the coupling line gap might be useful since the variation of the reactance due to V_g could be used to control the current without loss. In this case, the DC cut should be considered. For simplicity of the circuit without a DC cut, the method based on R_{ds} was used instead of C_{gs} in this paper.

V. CONCLUSION

One-way switching of the radiation pattern of an active antenna was achieved by controlling the gate bias of reactive FET which was used as an extra control circuit connected in shunt to the coupling line. By changing the bias voltage, the S_{11} of the input port of the reactive FET can be varied due to the variation of the reactance provided by the MESFET. This induces the change of boundary condition on the coupling line so that the one-way electronic beam-switching occurred. On the other hand, two-way switching phenomenon of the radiation pattern was achieved by controlling the gate bias or optical illumination of the MESFET connected in series to the coupling line. By changing the drain-to-source resistance of the MESFET electronically or optically, the oscillation mode of the active antenna can be changed to switch the radiation patterns. In either cases above, the switching operation was stable with the slight difference of the operating frequency between the sum and difference patterns.

The advantage of using the control circuit connected in shunt such as the reactive FET investigated in this paper is that it does not dissipate the energy if an ideal lossless reactive circuit is available since the current on the coupling line is controlled indirectly by the impedance change due to a reactive element. However, wide reactance variation range is essential for changing the boundary condition to achieve two-way switching in this type of circuit. Another disadvantage is that the control circuit based on the reactive FET is relatively large to realize the ideal reactance and accommodate the DC cut. On the other hand, the resistance control circuit placed across the coupling line gap has attained the two-way beam-switching by controlling the current with a large resistance variation. However, the use of the resistance variation has caused the dissipation of the power. The method has made the total circuit smaller than the one using the reactive FET.

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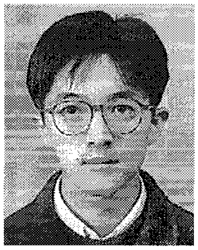

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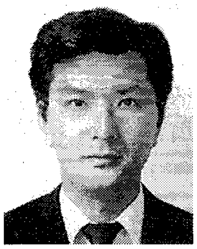

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He joined Technical Research and Development Institute, Japan Defense Agency in 1981 where he worked on millimeter-wave circuits and subsystems for remote sensing. In 1990, he was a Research Assistant at the University of Texas, Austin. From 1991 to 1993, he was a Graduate Student Researcher at University of California, Los Angeles. In 1994, he joined the faculty of Communications Engineering at Tokai University, Japan. His current research interests include microwave and millimeter-wave devices, circuits, antennas and active integrated antenna arrays. His group at Tokai University is included with the design, fabrication and measurements of millimeter-wave planar antenna arrays and active integrated antennas and their optical control. In addition, his group has been deveoping FET small signal and large signal models for optically controlled active integrated antennas and novel microwave simulators.

Dr. Kawasaki is a member of the Institute of Electronics, Information, Communication Engineers, Japan. He has several patents and published more than 30 papers.