Ultra-Wideband MMIC Active Power Splitters with Arbitrary Phase Relationships

Hideki Kamitsuna, *Member, IEEE,* and Hiroyo Ogawa, *Member, IEEE*

***Abstract*— Novel MMIC active power splitters, which allow arbitrary phase division over wide frequency ranges exceeding an octave in bandwidth, are proposed. An FET's inherent phase inversion properties together with phase adjustment circuits, e.g., common drain FETs followed by phase-shift transmission lines, can be successfully combined for broadband, arbitrary phase division. As an example of this technique, an MMIC active quadrature splitter has been designed and fabricated in a 1.1 mm × 0.7 mm chip area. A phase error of less than 5° with a magnitude imbalance of less than 1 dB has been demonstrated over a double-octave frequency range of 7.2–21.6 GHz. The MMIC active power splitter promises to make possible miniaturized, full MMIC signal processing components.**

I. Introduction

SIGNAL COMBINING/DIVIDING components, especially with phase relationships of 0°, 90°, and 180°, are fundamental functions in microwave and millimeter-wave circuits and systems. Miniaturizing such components with broadband characteristics is a key technology in realizing high-speed, intelligent microwave systems such as a phased array antenna system [1]. Therefore, considerable effort has been made to achieve MMIC signal control components such as phase shifters.

Hybrid couplers are often used for 90° and 180° power dividers or combiners in microwave circuits such as balanced mixers and amplifiers as well as phase shifters. Traditional couplers are constructed with several quarter-wavelength or longer transmission lines. Therefore, they require large-area MMIC chips and their bandwidths are limited owing to the utilization of such transmission lines.

On the other hand, active-element construction methods have reportedly overcome these problems. Recently, line-unified FETs (LUFETs) [1]–[4], which are effectively unified coplanar transmission lines in the FET electrode allocation, have been reported and ultra-wideband performance was achieved with FET-sized circuits. However, the phase division/combination relationship, which is determined by passive components, is limited to 0° and 180° only. Other phase division/combination functions such as 90° phase shifters, have not, to our knowledge, been achieved by such procedures.

In this paper, very small, ultra-wideband MMIC active power splitters with arbitrary phase relationships, which are based on the FET's inherent phase inversion properties together with phase adjustment circuits, are proposed. FETs followed by transmission lines as phase adjustment circuits allow us to achieve arbitrary (less than 180°) phase splitting characteristics over a wide frequency range that exceeds an octave in bandwidth.

MMIC active quadrature power splitters have been designed and fabricated as examples of the proposed circuits. A phase error of less than 5° with a magnitude imbalance of less than 1 dB has been demonstrated over a double-octave frequency range of 7.2–21.6 GHz. The chip size is only 1.1 mm × 0.7 mm. This paper describes the basic configuration and principles of the proposed wideband power splitters followed by the design and performance of MMIC active quadrature power splitters. Comparison of the MMIC active power splitters with conventional MMIC hybrid couplers is also made.

Manuscript received September 20, 1992; revised February 1, 1993.

The authors are with ATR Optical and Radio Communications Research Laboratories, Seika-cho, Kyoto 619–02, Japan.

IEEE Log Number 9211871.

II. Basic Configuration and Principle

The basic configuration of the proposed wideband active power splitter, an FET phase inverter followed by phase adjustment circuits, is shown in Fig. 1. The phase difference between the FET drain and source and different FET configurations such as common source FET (CSF) and common gate FET (CGF), can be utilized as phase inverters. However, their performance degrades at high frequency owing to parasitic capacitance [5], [6]. Fig. 2 shows a calculated example of phase difference performance between the FET drain (port ②) and source (port ③). The dashed lines represent the insertion phase of both $\angle S_{21}$ and $\angle S_{31}$. The solid line represents the phase difference $\angle S_{21} - \angle S_{31}$. These can be utilized as out-of-phase dividers only in the frequency range under than 5 GHz. The out-of-phase splitting performance gradually degrades as the frequency increases. If the phase shift components, which compensate for such phase offset, are connected at the output ports, wideband performance can be obtained. In this case, transmission lines can be utilized as phase shifters because their insertion phase characteristics are linear. The dotted line shown in Fig. 2 is the phase difference performance when transmission lines whose electrical length is 45° at 20 GHz are connected at the source terminal. Ultra-wideband (dc ~ 30 GHz) out-of-phase dividing performance is obtained with a very simple configuration.

To achieve wideband phase splitting performance (other than 180°), active power splitters with additional phase adjustment circuits are proposed as shown in Fig. 3. In this configuration, additional phase adjustment circuits, which consist of a capacitor, resistor, and common drain FET, are connected to each output port of the FET phase inverters,

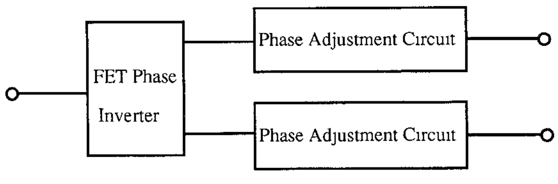

Fig. 1. Basic configuration of the proposed wideband active power splitter.

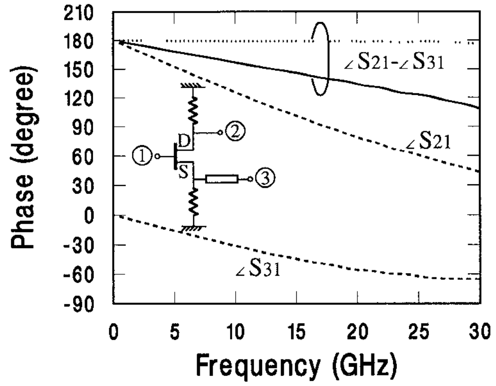

Fig. 2. Calculated example of the phase difference between the FET drain (port ②) and source (port ③). The dashed lines represent the insertion phase of both $\angle S_{21}$ and $\angle S_{31}$. The solid line represents the phase difference $\angle S_{21} - \angle S_{31}$. The dotted line represents the phase difference performance when transmission lines whose electrical length is 45° at 20 GHz are connected at the source terminal.

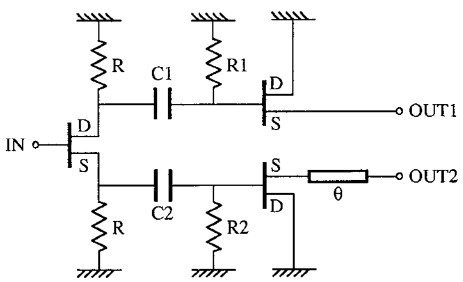

Fig. 3. Circuit diagram of the wideband active power splitter.

followed by phase-shift transmission lines. The degradation performance of FET phase inverters owing to parasitic capacitance can be utilized as arbitrary-degree (less than 180°) power splitters at a particular frequency as shown in Fig. 2. However, wideband performance, especially in the low-frequency range, is difficult to achieve by connecting transmission lines only. These additional circuits can drastically change the differential phase. Accordingly, the phase shift from the drain terminal of the FET phase inverter can be increased over that from the source terminal by C1•R1 making greater than C2•R2. Common drain FET configurations have been chosen because of their high-input and low-output impedance characteristics. Therefore, they allow us to rotate the phase significantly, as well as provide active matching [7]. These common drain FETs also assure the isolation of both output ports.

Fig. 4 shows the calculated phase difference between two output ports of the active 60°, 90°, and 120° power splitters with and without phase-shift transmission lines. The dashed lines represent those without transmission lines and the solid lines represent those with transmission lines. Each of the

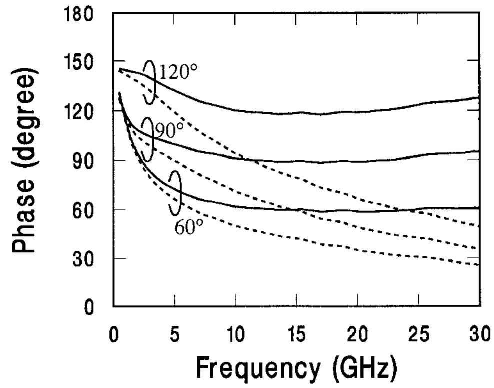

Fig. 4. Calculated phase difference between two output ports of the active 60°, 90°, and 120° power splitters. The dashed lines represent those without transmission lines and the solid lines represent those with transmission lines whose electrical length is, respectively, 25°, 40°, and 50° at 20 GHz for 60°, 90°, and 120° power splitters.

passive parameters, i.e., resistances of R, R1, and R2, capacitances of C1, C2 and transmission line electrical length of θ is optimized to achieve wideband phase splitting of 60°, 90°, and 120°, respectively, thus maintaining the magnitude balance. This configuration, compared with the FET phase inverters shown in Fig. 2, enables us to change phase differences significantly. Furthermore, ultra-wideband performance over a 1-octave bandwidth has been achieved by connecting simple phase-shift transmission lines whose electrical length is, respectively, 25°, 40°, and 50° at 20 GHz for 60°, 90°, and 120° power splitters. This wideband performance has been achieved with a very simple configuration that consists of three FETs, transmission lines, and other lumped components. Moreover, arbitrary (less than 180°) phase splitting performance over a 1-octave bandwidth can be obtained merely by optimizing the values of lumped elements and transmission line lengths.

It is thought that, because these circuits are constructed from active components, their performance is very sensitive to process parameter fluctuations. However, the proposed configuration is hardly affected by process fluctuation. This is due to the fact that process fluctuations of each FET-device parameter as well as passive components (capacitor, resistor) are almost the same in the monolithic integration. Therefore, it is expected that the phase rotation offset at each phase adjustment circuit caused by process fluctuations is canceled. An FET phase inverter with a reactive feedback element attached between the drain and the gate is one possible alternative means of adjusting the phase difference. However, the phase rotation performance of such configurations is barely restored due to the absence of compensation circuits like those proposed.

III. MMIC Active 90° Power Splitters

To verify the fundamental behavior, MMIC active 90° power splitters have been designed and fabricated in a 1.1 mm × 0.7 mm chip area. The circuit diagram and a photomicrograph of this circuit are shown in Fig. 5(a) and (b), respectively. This circuit has been fabricated using n-AlGaAs/InGaAs high-electron-mobility-transistors (HEMTs)

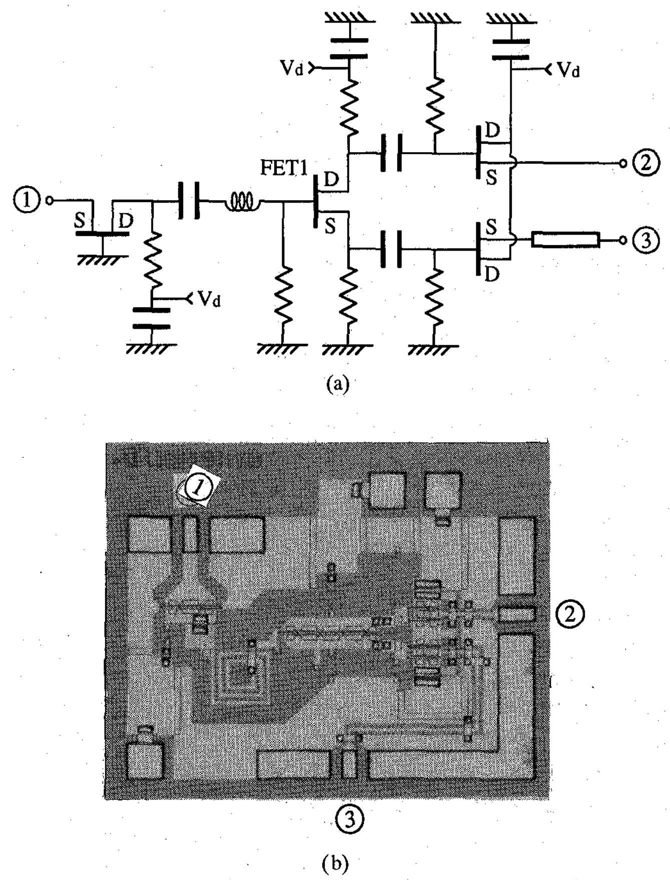

Fig. 5. Circuit diagram and photomicrograph of the MMIC active quadrature power splitter. (a) Circuit diagram. (b) Photomicrograph.

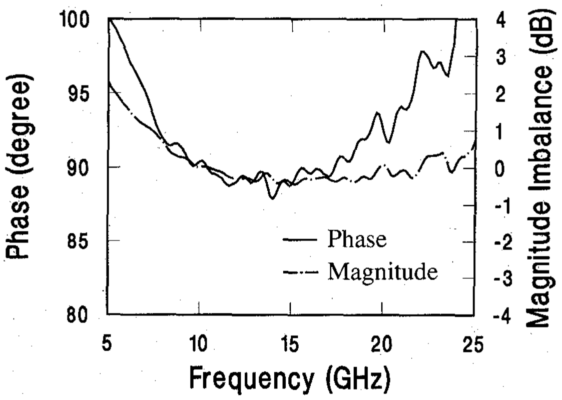

Fig. 6. The measured phase and magnitude differences from both output ports of the MMIC active quadrature power splitter.

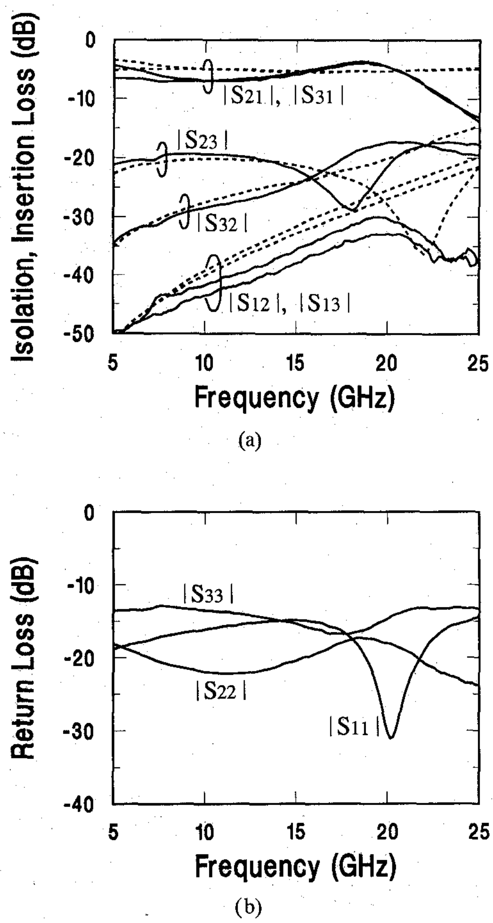

Fig. 7. The measured and predicted performances of the MMIC active quadrature power splitter. Solid lines represent measured values and dashed lines represent predicted values.

whose gate length is 0.25 μm and whose cut-off frequency is approximately 40 GHz. This 90° power splitter has a common-gate FET (CGF) at input port ① to achieve active matching [7]. The phase inverter FET (FET1) has 200-μm gate width and the other FETs have a 100-μm gate width. Coplanar waveguides (CPWs) whose center conductor width and gap width is 10 μm (corresponding to the characteristic impedance of 50 Ω) are utilized as final phase-shift transmission lines. A spiral inductor is utilized for broadband operation. The chip size can be reduced by using thin film microstrip (TFMS) lines [8], instead of CPWs, as final phase shifters.

Figs. 6 and 7 show performances of the MMIC active 90° power splitter. The measured performance was obtained using Cascade Microtech on-wafer probes and an HP8510 network analyzer. Drain biases are supplied through dc pads. Source biases are supplied through a wideband bias T and on-wafer probes attached at input port ① and output ports ② and ③ The source biases are approximately adjusted for a transconductance of 20 mS. Self bias was made at FET1. The power consumption is 84 mW.

Excellent 90° power splitting performance, i.e. a phase error of less than 5° with a magnitude imbalance of less than 1 dB, has been demonstrated in a double-octave frequency range from 7.2 to 21.6 GHz as shown in Fig. 6. In this frequency range, the measured performances are summarized as follows: insertion loss ($|S_{21}|, |S_{31}|$) is better than 7 dB, isolation between the input port and both output ports ($|S_{12}|, |S_{13}|$) is better than 30 dB, and between both output ports ($|S_{23}|, S_{32}|$) is better than 17 dB. The return losses ($|S_{11}|, |S_{22}|, |S_{33}|$) are better than 15 dB, 17dB, and 13 dB, respectively. Measured transmission characteristics are somewhat degraded over 20 GHz compared with the predicted values. This is due to the spiral inductor's over-peaking. However, by reducing the bandwidth, transmission gains, rather than losses, can be obtained. If this quadrature splitter is applied to the image rejection mixer, its phase- and magnitude errors are sufficiently

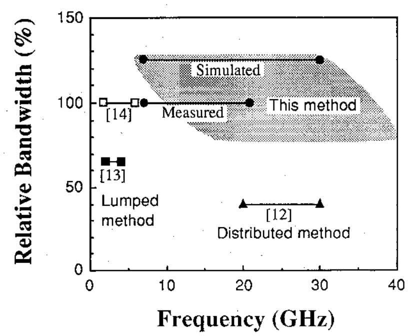

Fig. 8. Comparison of MMIC active quadrature power splitters with reported results. Circles represent our results. Squares represent the lumped method (filled [13] and open [14]). Triangles represent the distributed method [12].

small to achieve an image rejection in excess of 20 dB [9] over the obtained double-octave RF input frequency range.

IV. Discussion

In this section, the proposed active power splitters are compared with conventional microwave quadrature hybrids. Branch-line and coupled-line-type couplers have been utilized as 90° power splitters at microwave- and millimeter-wave frequencies. Branch-line hybrids are often used as 90° power splitters in MMICs because of their ease of design and fabrication. Several techniques [10], [11] to reduce the circuit size for adaptation to MMICs, have been reported. However, the bandwidth is narrow (less than 10%) and difficult to adapt to MMICs, especially in the low-frequency range up to the X-band. Coupled-line structure performance is inherently wideband. Recently, broad-side couplers [12] which operate at 20–30 GHz using multilayer MMIC technologies, have been reported. However, the fabrication of such structures is complicated and further wideband operation is difficult to achieve. It is also very difficult to adapt these structures for use in the low-frequency range below the X-band due to significant conductor losses [8].

Wideband 90° power splitting performance has also been achieved by combining lumped-element, high-pass, and low-pass filters [13], [14]. These methods require several spiral inductors especially for broadband operation and are wasteful of MMIC chip area. Furthermore, high-frequency operation is difficult owing to the utilization of spiral inductors.

A comparison of the reported results for wideband quadrature splitters and our results are summarized in Fig. 8. As shown in this figure, matchless wideband performance with a relative bandwidth of 100% has been achieved at microwave frequencies. Although the proposed active quadrature splitter, which is based on the FET phase inverter, does not readily achieve low-frequency operation, ultra-wideband performance, from several GHz to the transistor's cut-off frequencies, is possible with very small size. Therefore, ultra-wideband functional MMICs such as image rejection mixers, QPSK modulators and 360° continuous phase shifters [1] can be achieved using the demonstrated active quadrature power splitters.

V. Conclusion

Very small, ultra-wideband MMIC active power splitters, which are based on the FET's inherent phase inversion properties together with phase adjustment circuits, are proposed. An FET phase inverter and phase adjustment circuits, i.e., common drain FET's followed by phase-shift transmission lines are successfully combined for a broadband, arbitrary phase division. As an example of these circuits, the MMIC active quadrature power splitter has been designed and fabricated in a chip area of 1.1 mm × 0.7 mm. Excellent 90° power splitting performance, i.e. a phase error of less than 5° with a magnitude imbalance of less than 1 dB, has been demonstrated over a double-octave frequency range of 7.2–21.6 GHz. This excellent performance cannot be realized by conventional procedures based on distributed or lumped passive elements. This wideband performance has been achieved using a very simple configuration which consists of three FETs, transmission lines, and other lumped components. Moreover, arbitrary phase splitting performance such as 60° and 120° can be obtained merely by optimizing the values of the lumped elements and transmission line lengths. Therefore, the MMIC active power splitter promises to realize miniaturized full MMIC signal processing components owing to its small size and wideband performance as well as a design flexibility that allows arbitrary phase splitting characteristics.

Acknowledgment

The authors would like to thank Drs. K. Habara, Y. Furuhama, and E. Ogawa for their continuous support and encouragement.

References

[1] S. Hara and T. Tokumitsu, "Very small control modules with line unified FET configuration for array processing," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-39, pp. 117–123, Jan. 1991.

[2] T. Tokumitsu, S. Hara, and M. Aikawa, "Very small ultra-wideband MMIC magic T and applications to combiners and dividers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-37, pp. 1985–1990, Dec. 1989.

[3] T. Tokumitsu, S. Hara, T. Takenaka, and M. Aikawa, "Divider and combiner line-unified FETs as basic circuit function modules—Part I," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-38, pp. 1210–1217, Sept. 1990.

[4] T. Tokumitsu, S. Hara, T. Takenaka, and M. Aikawa, "Divider and combiner line-unified FETs as basic circuit function modules—Part II," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-38, pp. 1218–1226, Sept. 1990.

[5] S. Hara, T. Tokumitsu, and M. Aikawa, "Novel unilateral circuits for MMIC circulators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-38, pp. 1399–1406, Oct. 1990.

[6] T. Hiraoka, T. Tokumitsu, and M. Akaike, "A miniaturized broadband MMIC frequency doubler," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-38, pp. 1932–1937, Dec. 1990.

[7] K.B. Niclas, "Multi-octave performance of single-ended microwave solid-state amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 896–908, Aug. 1984.

[8] T. Hiraoka, T. Tokumitsu, and M. Aikawa, "Very small wide-band MMIC magic Ts using microstrip lines on a thin dielectric film," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-37, pp. 1569–1575, Oct. 1989.

[9] S. A. Maas, *Microwave Mixers.* New York: Artech, 1986, pp. 249–251.

[10] T. Hirota, A. Minakawa, and M. Muraguchi, "Reduced-size branch-line and rat-race hybrids for uniplanar MMICs," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-38, pp. 270–275, Mar. 1990.

[11] H. Nakamoto, T. Hiraoka, and T. Tokumitsu, "Very small multilayer MMIC hybrids using polyimide films," in *3rd Asia-Pacific Microwave Conference Proc.,* 1990, pp. 1113–1116.

[12] I. Toyoda, T. Hirota, T. Hiraoka, and T. Tokumitsu, "Multilayer MMIC branch-line coupler and broad-side coupler," in *IEEE Microwave and Millimeter-Wave Monolithic Circuits Symp. Dig.,* 1992, pp. 79–82.

[13] J. Staudinger and W Seely, "An octave bandwidth 90° coupler topology suitable for MMICs," *Microwave J.,* pp. 117–130, Nov. 1990.

[14] F. Ali and A. Podell, "Design and applications of a 3:1 bandwidth GaAs monolithic spiral quadrature hybrid," in *IEEE GaAs IC Symp. Dig.,* 1990, pp. 279–282.