LOSSLESS, BROADBAND MONOLITHIC MICROWAVE ACTIVE INDUCTORS

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ABSTRACT

Lossless, broadband microwave active inductors are proposed for general purpose use in microwave circuits. These active inductors operate in a wide frequency range with very low series resistance. Furthermore, the inductance value can be controlled by the external control voltage.

INTRODUCTION

In MMIC design, spiral inductors are often used to reduce chip size. However, the area of a spiral inductor is still rather large compared to that of other lumped elements. It is also difficult to realize a broad band spiral inductor, especially one of high inductance, because of stray capacitances. We previously proposed a microwave active inductor comprised of a cascode FET and a feedback resistor, at the last symposium [1], for realizing smaller-sized, wide-band MMICs. However, because it includes an equivalent series resistance with a value approximately equal to the reciprocal of the GaAs FET transconductance, MMIC function blocks where the active inductor can be applied are limited.

In this paper, new types of microwave active inductors are proposed. One advantage of the newly proposed active inductors is low loss or lossless characteristics due to replacement of the feedback resistor to GaAs FETs, as well as the following features realized in the previously proposed active inductor:

1. Very high frequency operation.
2. Small size independent of the inductance value.

CONFIGURATION AND PERFORMANCE

Previously Proposed Active Inductor

Configuration and operation : The schematic of the previously proposed microwave active inductor is shown in Fig.1 to explain the very high frequency

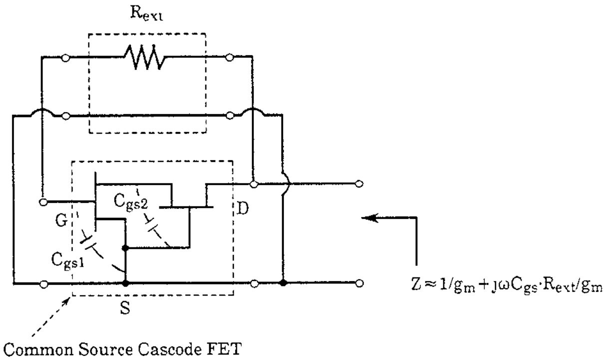

Fig.1 Circuit Configuration of the Previously Proposed Active Inductor

operation of the active inductors. This active inductor is composed of a common source cascode FET and a parallel feedback resistor (R_{ext}), where very high frequency operation is achieved by cancelling the dominant parasitic capacitances in each FET of the cascode FET.

When an FET is assumed to be the combination of only the transconductance g_m and the gate-source capacitance C_{gs}, the impedance Z of this active inductor is given by equation (1) :

$$Z = \frac{1 + j\omega C_{gs1} R_{ext}}{g_{m1} + j\omega \left[C_{gs1} - C_{gs2}\left(\frac{g_{m1}}{g_{m2}}\right) + \omega^2 C_{gs2}\left(\frac{C_{gs1} C_{gs2}}{g_{m2}^2}\right) \right]} \quad (1)$$

where suffixes 1 and 2 correspond to the first and second FET, respectively, in the cascode FET. When the cascode FET is composed of the same FETs with the same g_m and C_{gs}, the gate-source capacitances C_{gs1} and C_{gs2} cancel each other out. This is why this active inductor operates over a wide frequency range. The operation up to 10GHz was confirmed through measurements[1]. The resonant frequency of these active inductors increases further as the FET's high frequency characteristics improve. An equivalent circuit of this active inductor can be approximated by a resistor ($1/g_m$) and an inductor ($C_{gs}R_{ext}/g_m$) in series connection.

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Linearity and distortion : As a result of a simulation using commercially available nonlinear CAD software, it was concluded that the maximum handling power without distortion, P_{Lmax}, of the active inductor is represented as follows [2] ;

$$P_{Lmax} = K/2 \times I_{dss} \times (V_{D2} - V_{G2}) \qquad (2)$$

where I_{dss} is the saturation current of the FET, V_{D2} and V_{G2} are the DC bias voltage of the drain and gate of the 2nd FET in the cascode FET, and K is a coefficient, 2/3 in this active inductor. When the input voltage is larger than (V_{D2} - V_{G2}), the gate voltage can be larger than the drain voltage and the input current is distorted.

Noise : A broad band active matching amplifier, which used the active inductors, was also demonstrated at the last symposium[1]. With regard to that amplifier, the noise analysis is examined in two cases; the FETs in the active inductors had noise parameters or not. As a result, the former case is 1dB worse than the latter case.

Newly Proposed Active Inductor (Type (a))

Configuration and operation : The schematic of the newly proposed active inductor is shown in Fig.2. A common gate FET is used in the feedback circuit instead of a resistor. The admittance Y of this active inductor is approximately represented by equation (3):

$$Y = g_{mf}\left(1 - \frac{C_{gs2}\, g_{m1}}{C_{gs1}\, g_{m2}}\right) + \frac{g_{m1}\, g_{mf}}{j\omega C_{gs1}} \qquad (3)$$

where suffixes 1 and 2 correspond to the first and second FET in the common source cascode FET, and suffix f corresponds to the common gate FET. When the common source cascode FET is composed of the same FETs with the same g_m and C_{gs}, the conductance becomes zero in eq.(3). As a result, this circuit functions as a lossless inductor whose impedance value Z is represented by equation(4):

$$Z = j\omega \frac{C_{gs}}{g_m\, g_{mf}} \qquad (4)$$

Calculated performance : The characteristics of a conventional spiral inductor, the previously proposed active inductor, and the newly proposed active inductor are compared in Fig.3. The broken line is for a spiral inductor, the chained-dotted line is for the previously proposed active inductor, and the solid line is for the newly proposed active inductor which includes a common gate FET feedback circuit. The impedance characteristics are compared in Fig.3(a). The value of each inductor is nearly 3.5nH at 1GHz. The spiral inductor is assumed to be fabricated on a 200µm thick GaAs substrate, and has a size of 300µm×300µm, a line width of 10µm, and an Au line thickness of 2µm. The active inductor characteristics are calculated using the parameters for a typical FET which has a cut-off frequency f_t of 20GHz. The value of the feedback resistor or the gate width of a feedback FET is designed for an inductance value of 3.5nH. The newly proposed active inductor has much lower loss characteristics compared with the previously proposed active inductor, and the series resistance values are nearly equal to that of the spiral inductor.

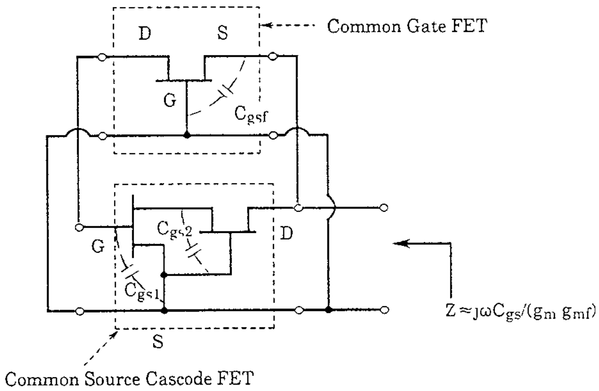
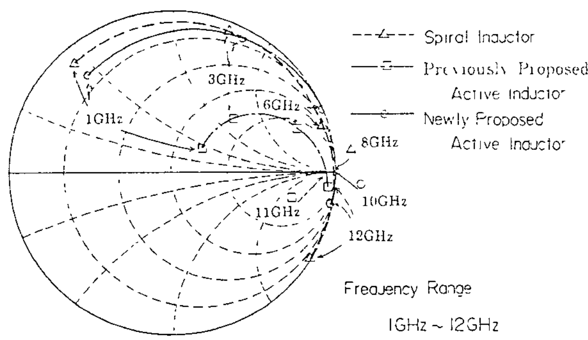
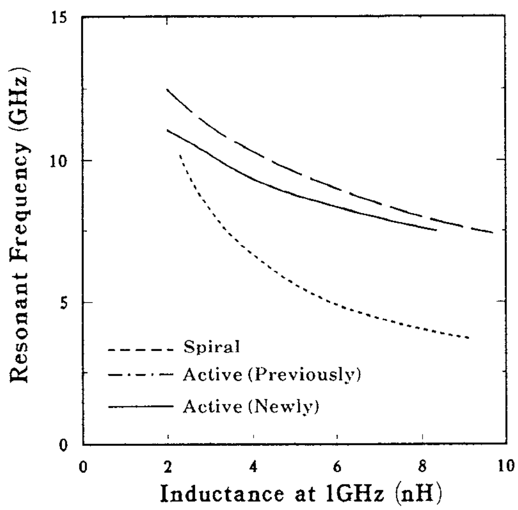


Fig.2 Circuit Configuration of the Newly Proposed Active Inductor (Type(a))



(a) Impedance



(b) Resonant Frequency

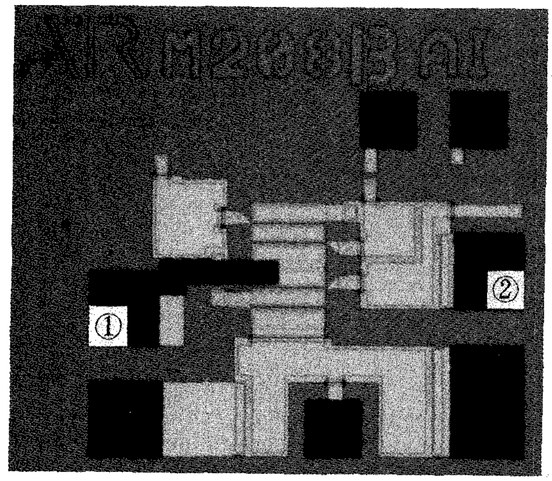
Fig.3 Comparisons Among the Inductors

The resonant frequency, which is the maximum inductor operating frequency, is compared in Fig.3(b) to the inductance value at 1 GHz. As shown in Fig.3(b), the operating frequency range of the newly proposed active inductor is close to that of the previously proposed active inductor, as well as higher than that of a spiral inductor, especially in the high inductance region. Furthermore, the operating frequency is extended as the FET"s are improved [1].

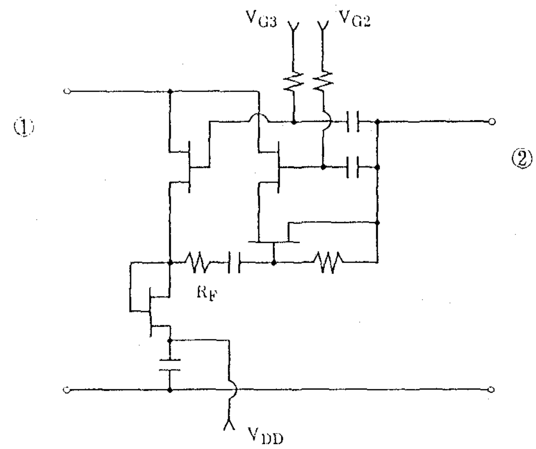
Fig.4 shows the impedance change caused by the gate width of the feedback FET, where the gate width of the common source cascode FET is constant, 100μm. As shown in Fig.4, the inductance value and the gate width are inversely proportional, which is implied in the equation (4). And the newly proposed active inductor also has a loss, because an actual FET has many parasitics not considered in the approximation used in eq.(3) and (4). However, the loss is much lower than that of the previously proposed active inductor.

Linearity and distortion : As with the resistor feedback active inductor, the current is distorted when the input voltage is larger than (V_{S3}-V_{G3}). Here, V_{S3} and V_{G3} are the DC bias voltage of the source and gate of the feedback FET.

Experiment result : A photograph of a fabricated GaAs monolithic active inductor and a circuit configuration diagram are shown in Fig.5. Four 0.5μm×100μm single gate ion implanted FETs with a typical cutoff frequency of 20GHz are employed. One FET is used for DC biasing. The measured and predicted impedance of the active inductor are shown in Fig.6, where the port ② is grounded. The loss is slightly higher than the value predicted in Fig.4. This is because the FET for DC bias does not offer infinite impedance for the active inductor. The Q value is about 2 at 3GHz. Higher Q value can be obtained by using the wider gate FET as cascode FET.



(a) Photograph of the Chip



(b) Circuit Configuration

Fig. 5 Configuration of the Active Inductor

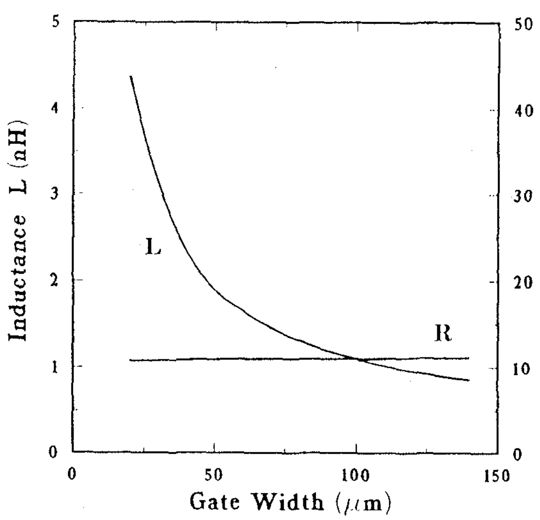


Fig.4 Impedance at 1GHz vs. Gate Width of Feedback FET

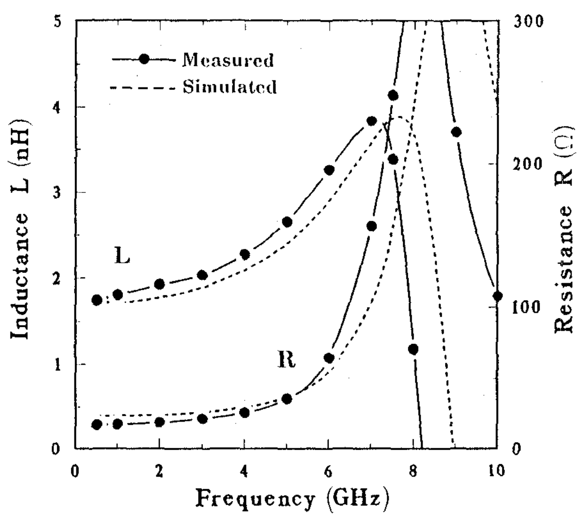


Fig.6 Impedance-frequency Characteristics

Newly Proposed Active Inductor (Type (b))

Configuration and operation : The schematic of the other type of active inductor is shown in Fig.7. A common gate cascode FET or a common gate dual gate FET is used for the feedback circuit. In this case, the admittance Y of the parallel connection of a common source cascode FET and a common gate cascode FET is expressed approximately as follows :

$$Y = -g_m \frac{C_{gsf}}{C_{gs}} + \frac{1}{j\omega\left(\frac{C_{gs}}{g_m g_{mf}}\right)} \qquad (5)$$

Here, g_{mf} and C_{gsf} are, respectively, the transconductance and the gate-source capacitance of each FET in the common gate cascode FET. Equation (5) shows that the equivalent circuit of this active inductor is a parallel connection of a negative resistor ($-C_{gs}/C_{gsf} \cdot g_m$) and an inductor ($C_{gs}/g_m \cdot g_{mf}$). Therefore, if a shunt resistor with a value of $C_{gs}/C_{gsf} \cdot g_m$ is connected as shown in Fig.7, this circuit functions as a lossless inductor whose value is $C_{gs}/g_m \cdot g_{mf}$. Furthermore, the inductance value can easily be controlled by the external control voltage V_c supplied to the second gate of the feedback cascode FET, because g_{mf} is controlled by V_c.

Calculated performance : Cascode FET feedback type active inductor can be lower loss compared with CGF feedback type as shown in eq.(3) and (5). Furthermore, the inductance value can be changed by changing the voltage of the 2nd gate of the feedback cascode FET. The impedance change of the active inductor is shown in Fig.8, where the control voltage V_c is changed. These curves are obtained from the S-parameters calculated by using the "Curtice model" in "mwSPICE", where a 150μm gate width common source cascode FET and a 50μm gate width common gate cascode FET are used. By changing the control voltage, the inductance value changes from 2nH to 3nH while the series resistance change is only from 2Ω to 10Ω.

Stability : As mentioned above, resistor R_s is connected for stability. Because the resistor value is set to make the active inductor stable in all frequencies, the active inductor is a little lossy at some frequency points. However the loss is still lower than that of the CGF feedback active inductor.

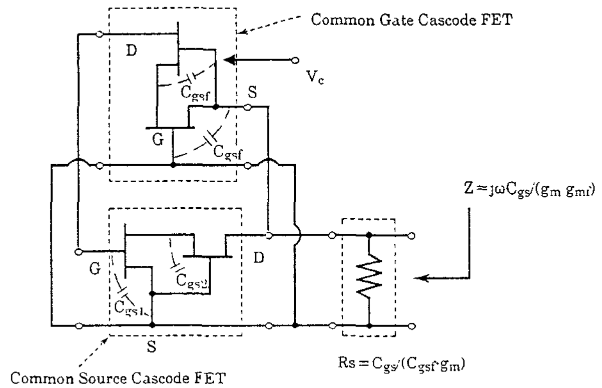


Fig.7 Circuit Configuration of the Newly Proposed Active Inductor (Type(b))

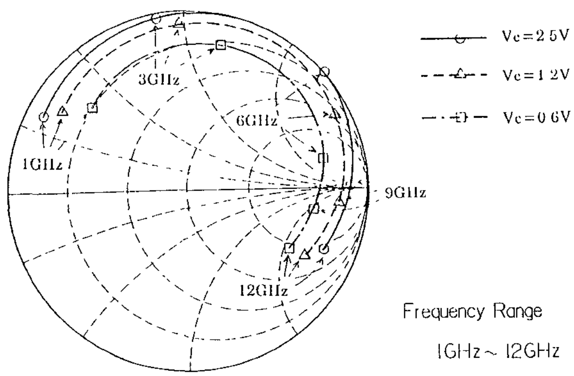


Fig.8 Impedance Change of the Active Inductor to the Gate Bias

CONCLUSION

Low loss microwave active inductors have been newly proposed. These active inductors are composed of a common source cascode FET and a feedback FET which is a common gate FET or a common gate cascode FET. The loss can be less than 1/8 the loss of the previously proposed active inductor. Additionally, these active inductors are broadband and voltage controllable. These features should prove valuable in designing smaller and more efficient microwave ICs.

ACKNOWLEDGMENTS

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References:

[1] S. Hara, et al., "Broad Band Monolithic Microwave Active Inductor and Application to a Miniaturized Wide Band Amplifier," IEEE 1988 Microwave and Millimeter-wave Monolithic Circuits Symposium Digest, pp.117-120, 1988.

[2] T. Tokumitsu, et al., "High Power Properties of the Active Inductor," National Convention Record, Autumn 1988, IEICE, C-352.