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A Monolithic Tunable High-Q InAlAs/n⁺-InP-HFET Resonator

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Abstract

In this paper we propose and demonstrate a novel monolithic active resonator network for an integrated band-pass filter application. The resonator's natural frequency and Q factor are electronically tunable. The resonator circuit was fabricated and tested in a MOCVD-grown InAlAs/n$^+$-InP-Heterostructure FET (HFET) process containing two levels of Au metal interconnect, MIM capacitors, mesa etched resistors and HFET diodes. The InP active resonator network achieved a natural frequency resonance of 7.7 GHz and a Q factor of over 3000. This represents two orders of magnitude improvement over prior art.

Introduction

Bandpass filters operating in the 1-to-10 GHz frequency range employ high-Q resonators to achieve high selectivity. The passive LC networks, dielectric resonators, and cavity resonators typically used in this frequency range are physically large and require mechanical tuning and cannot easily be integrated with electronic circuits. Active filter topologies based on operational amplifiers have not been used because of the necessary high gain and bandwidth requirements of the operational amplifier [1]. Recent monolithic tunable active inductors based on gyrator circuits have demonstrated Q values of only 10 to 65 [2].

In this paper we propose a novel monolithic active resonator circuit suitable for integrated band-pass filters. We implement the resonator in an InP HFET technology. The InAlAs/n$^+$-InP HFET active resonator circuit represents two orders of magnitude improvement over prior art.

Circuit Design

Our resonator circuit is a unique topology that is based on a circulator architecture with active lumped elements rather than passive distributed waveguide components. Our active resonator circuit is composed of four stacked transistors, J_1 - J_4, with capacitor feedback coupling as shown in Fig. 1. The simplified small-signal equivalent circuit of this network is analogous to an active circulator (see Fig. 2). The lumped-element equivalent circuit of our active resonator is functionally equivalent to a passive parallel LC network shunted by a negative resistance. The network's natural resonance can be shifted coarsely by placing an additional shunt capacitor at the input. An active load resistor R_Q is used to cancel the circuit's negative resistance and make the network either lossless ($R_Q \| R_R = \infty$) or matched to a 50 ohm ($R_Q \| R_R = 50\ \Omega$) transmission line impedance.

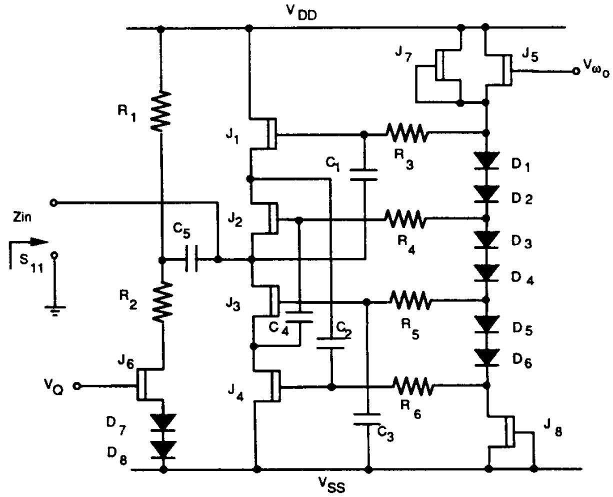

Fig. 1 InP HFET active resonator circuit with tunable natural frequency ($V\omega_0$) and Q factor (V_Q).

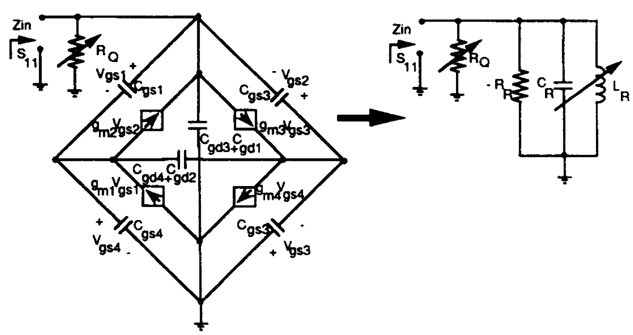

Fig. 2 Small-signal equivalent of active resonator circuit and functional equivalent circuit.

The resonator's frequency is finely tuned by simultaneously modulating g_{m1} - g_{m4} through the bias voltage action of source follower J_5 and diode level shifters D_1 - D_6. An increase in an external $V\omega_0$ produces a linear increase in V_{DS1} - V_{DS4} and a corresponding increase in g_{m1} - g_{m4}, which shifts the resonance to a higher frequency. The resonator's Q factor is tuned by modulating the channel resistance of J_6. Increasing an external V_Q adds an additional positive resistance in shunt with the resonator which is used to cancel the network's inherent negative resistance.

Fabrication Process Technology

Achieving high Q of the resonator circuit at high frequencies requires a process technology that has low parasitic capacitance and resistance, good device matching, and high f_T. Our novel InAlAs/n^+-InP HFET circuit technology employs InP both as the channel layer and as a selective etch-stop layer [3]. This provides simultaneously excellent breakdown voltage, high current, and low threshold voltage variation (σV_{th} = 13 mV).

To the basic process described in reference [3], our process has added PECVD SiO_2-assisted lift-off for all metals as well as spin-on-glass device passivation that also serves as an intermetal dielectric isolation (see Fig. 3). The gate metal serves as the bottom plate of the MIM capacitor and the interconnect metal serves as the top plate of the MIM capacitor. The resistors are implemented using the whole epitaxial structure with the heavily doped cap unrecessed. The resistor mesas are etched during the same process step as the transistors. The nominal sheet resistance of the resistors is 50 Ω/sq. The diodes are HFETs with the source and drain shorted.

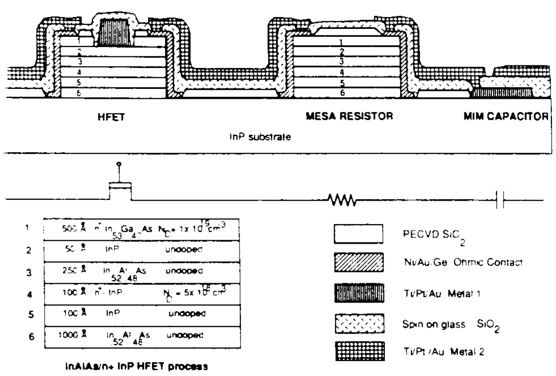

Fig. 3 InAlAs/n^+-InP-channel-HFET process including two levels of Au metal interconnect, mesa-etched resistors, and MIM capacitors.

Our HFET design based on an undoped pseudoinsulator and a thin highly-doped channel has shown promise for a variety of microwave applications due to its high current linearity over broad gate swing, large breakdown voltage, and low frequency dispersion [4]. Discrete L_g = 1.0 μm InAlAs/n^+-InP HFET's fabricated simultaneously with the resonator achieve g_m and $I_{D,max}$ values of 180 mS/mm and 450 mA/mm, respectively, together with an average breakdown voltage of 8 V (at I_D = 1 mA/mm) and f_T of 11-13 GHz (see Fig. 4).

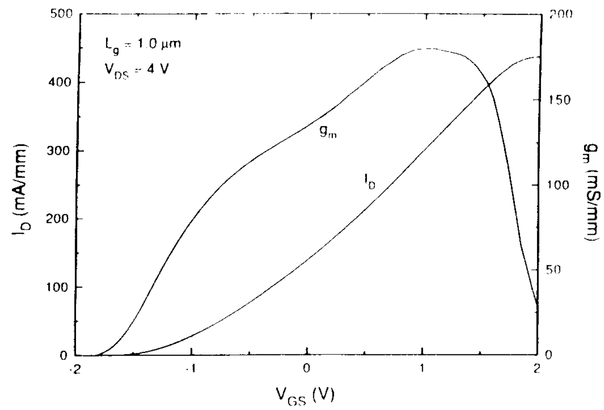

Fig. 4 InAlAs/n^+-InP-channel-HFET I_D and g_m versus V_{GS} for a transistor with L_g = 1.0 μm and biased at V_{DS} = 4V.

Experimental Results

The resonator was implemented using L_g = 1.0 μm HFETs in a 600 μm x 600 μm area as shown in Fig. 5. After fabrication, the resonator was cleaved, packaged and mounted on a microstrip printed circuit board. An HP 8510 network analyzer was used in to measure S_{11} in the configuration shown in Fig. 6. The resonator is biased with ± 4.5 volt power supplies with a power consumption of 22.4 mW.

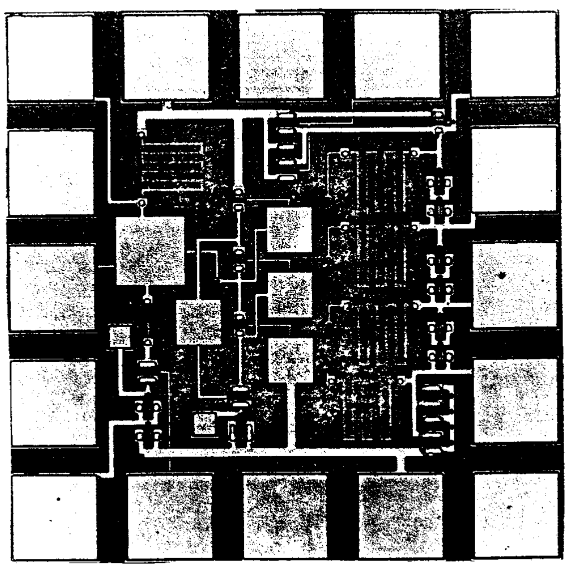

Fig. 5 Photomicrograph of the InP HFET resonator die.

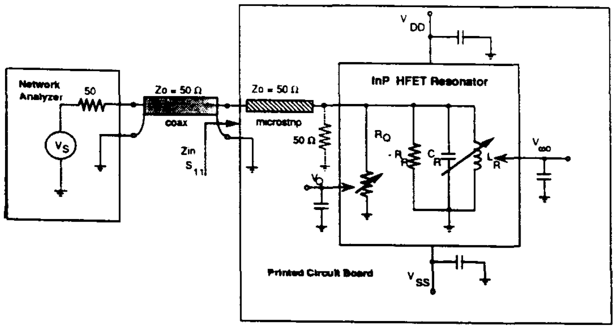

Fig. 6 Resonator test setup containing InP HFET active resonator driven by an HP 8510 network analyzer.

The S_{11} response of the resonator over a 20 GHz bandwidth shows a single resonance at 7.73 GHz with an out-of-band ripple smaller than 8 dB as shown in Fig. 7. For an optimized bias of V_Q = 2.323 V and $V_{\omega o}$ = 4.031 V, an $|S_{11}|$ minimum of -87 dB with a Q of 15,000 was measured (see Fig. 8). This data represents over two orders of magnitude improvement in Q over prior art. The value of Q, where $Q=f_0/BW_{3dB}$, was extracted from 3dB bandwidth of the resonance measured as the phase angle changes from +45° to -45°. This result was obtained by selecting V_Q such that $R_Q||R_R$ = 50 Ω. The same result (not shown) was obtained by placing an additional external resistor of 50 Ω in parallel and selecting $R_Q||R_R = \infty$. This confirms that the network can be made lossless. Additionally, this result shows that the resonator can be biased to produce a desired value of internal negative resistance. In a band-pass filter topology the resonator can be placed either in the feedback path of an amplifier with the resonator biased at a low positive resistance or isolated between two amplifiers and the resonator biased at the lossless point $R_Q||R_R = \infty$.

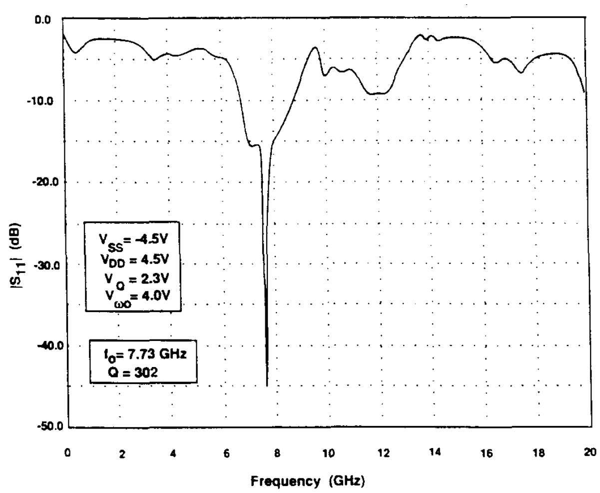

Fig. 7 $|S_{11}|$ of InP HFET active resonator from 45 MHz to 20 GHz. Measured minimum of $|S_{11}|$ is -47 dB corresponding to a Q of 302.

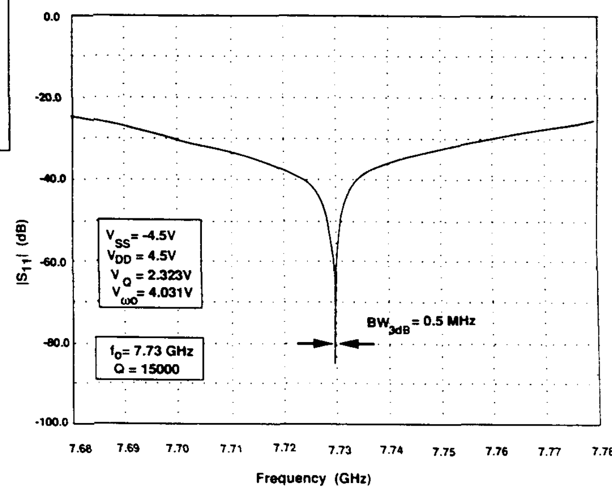

Fig. 8 $|S_{11}|$ of InP HFET active resonator from 7.68 to 7.78 GHz with an optimized bias. Measured minimum of $|S_{11}|$ is -87 dB. The Q is 15,000.

The tunability of the resonance frequency was demonstrated by increasing the natural frequency, ω_o, by 20 MHz through a 0.5 volt change in external $V\omega_o$, as shown in Fig. 9. The natural frequency of the resonance is proportional to the g_m of the four stacked transistors; an increase in g_m produces a corresponding positive shift in ω_o. Our HFET displays a relatively broad plateau of g_m versus V_{GS} (see Fig. 4). This results in the observed limited tuning range of the resonance. The Q factor was also tuned from 10 to 3000 with a 2-volt change in V_Q, as shown in Fig. 10. The V_Q and $V\omega_o$ control voltage of the resonance are correlated and must be simultaneously adjusted to achieve constant Q factors at different center frequencies.

The resonator circuit was simulated in both nonlinear (SPICE) and linear (LIBRA) circuit simulators containing models developed for our InP HFET process. Both these simulations show a natural resonance at 8.0 GHz (see Fig. 11).

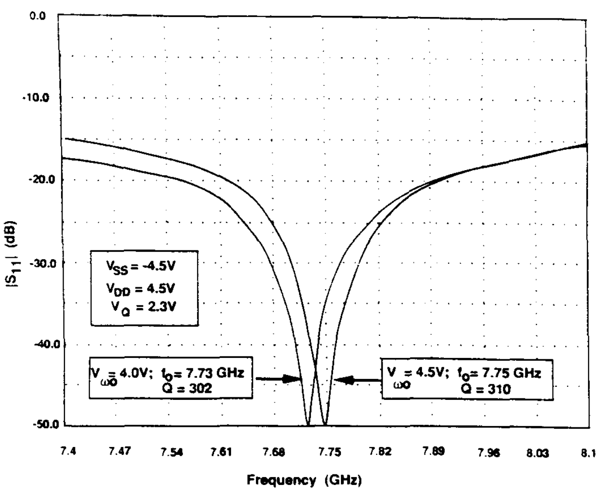

Fig. 9 Demonstration of InP HFET active resonator natural frequency tuning capability. A natural frequency increase of 20 MHz corresponds to a 0.5 volt increase in $V\omega_0$.

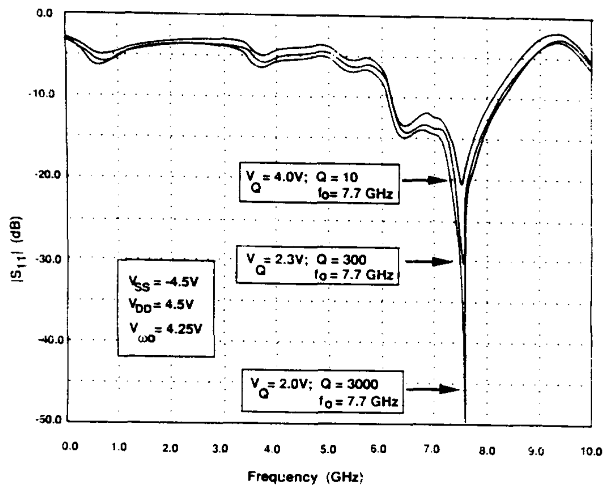

Fig. 10 Demonstration of InP HFET active resonator Q factor tuning capability. A Q factor increase from 10 to 3000 corresponds to a 2 volt increase in V_Q.

Conclusion

In summary, we have proposed and demonstrated a novel monolithic tunable active resonator circuit on an InP HFET process. A resonance with a Q of over 3,000 has been obtained at a frequency of 7.7 GHz. Our circuit demonstrates improvement in the state of the art of monolithic active circuit resonators by two orders of magnitude. Bandpass filters using this tunable active resonator as a building block show promise in achieving high selectivity for a wide variety of microwave applications including cellular radio, GPS, and RADAR systems.

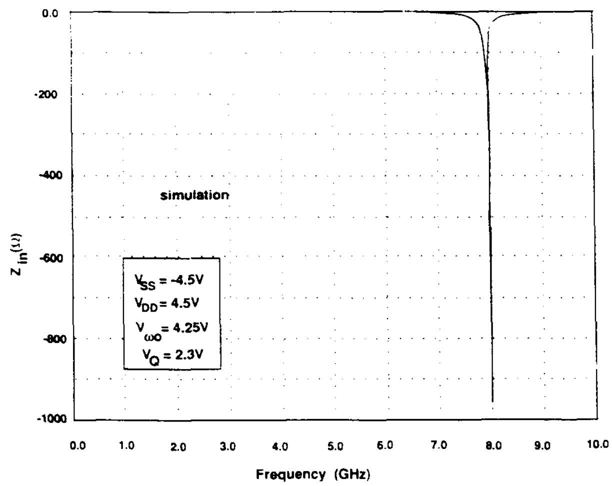

Fig. 11 Z_{in} SPICE simulation of unloaded ($R_Q = \infty$) InP HFET active resonator.

Acknowledgments

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References

[1] R. Schaumann and C.F. Chiou, "Design of Integrated Analog Active Filters," in *Proc. 1981 Europe Conf. Circuit Theory Des.*, p. 407, The Hague, The Netherlands, Aug. 1981

[2] S. Hara, T. Tokumitsu, M. Aikawa, "Lossless Broadband Monolitihic Microwave Active Inductor," IEEE *Trans. Microwave Theory Tech.*, Vol. 36, No. 12, p.1979, December 1989.

[3] D. R. Greenberg, J. A. del Alamo and R. Bhat, "A Recessed-Gate InAlAs/n^+-InP HFET with an InP Etch-Stop Layer," IEEE *Electron Device Lett.*, Vol. 13, No. 3, p. 137, 1992.

[4] D. R. Greenberg, J. A. del Alamo and R. Bhat, "A Pseudomorphic AlGaAs/n^+-InGaAs Metal-Insulator-Doped Channel for Broad-Band, Large-Signal Applications," IEEE *Electron Device Lett.*, Vol. 12, No. 8, p. 436, 1991.