NARROW-BAND MMIC FILTERS WITH AUTOMATIC TUNING AND Q-FACTOR CONTROL

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ABSTRACT

Narrow-band, active MMIC filters are demonstrated at X-band. Results are presented for both band-pass and notch circuits fabricated using standard GaAs MESFET processes. A novel Master-Slave control circuit provides compensation for fluctuations in fabrication process and operating temperature, and it enables the filter to accurately track a reference signal.

INTRODUCTION

Many microwave systems require fixed-frequency and/or tunable narrow-band filters for functions such as interference rejection, mixer image/LO suppression, spurious harmonic rejection, and frequency multiplexing. Integration of such filters in MMIC form offers the possibility of substantial system size and cost reduction. However, due to their small physical size, the Q-factor of passive MMIC components tend to be very low. It is therefore necessary to use active circuit approaches to implement monolithic, narrow-band filters with acceptable performance.

Several monolithic implementations of active microwave filter circuits have been reported, including broad-band (>10% bandwidth) designs [1,2], and narrow-band [3,4] ones which used RC network structures at L-band. This paper describes our approach for implementing narrow-band filters at X-band using GaAs MESFET devices to enhance the Q-factor of passive resonant circuits [5-7]. In contrast to the distributed, hybrid resonant structures described in [6,7], we use lumped-element (LC) tank networks to achieve a smaller circuit size compatible with low-cost monolithic integration.

Active, narrow-band MMIC circuits are usually considered to be impractical due to their intrinsic sensitivity to operating temperature and fabrication process variations. We show here that it is possible to overcome these problems using a master-slave control circuit loop configuration. This type of circuit has been reported previously [8],[9] for active filters operating at a few MHz, implemented with silicon IC technology. However, we use a novel, simpler approach to generate both frequency and Q-factor control signals.

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FILTER DESIGN

We designed both active band-pass and band-reject (notch) MMIC filters. Figure 1 shows the basic topology for the parallel LC band-pass filter sections. It consists of a dual-gate FET with the first gate connected to a pair of inductors to generate the equivalent of a negative resistance. This resistance is adjusted through the voltage on the second gate so as to cancel the passive component losses, thereby obtaining an effective unloaded Q-factor (Qu) close to infinity for the resonant circuit. Tuning is accomplished through a pair of back-to-back varactor diodes to minimize distortion. A three-pole filter is implemented by cascading three such sections using capacitive coupling. Capacitive coupling is also used at the filter input/output ports to provide the required impedance transformation to 50 Ohms. As these coupling capacitors are of different size than the inter-resonator ones, a suitable compensation capacitor is connected across the varactor diode pair in each section, as shown in Figure 1. In other respects, all three resonators in the band-pass filter are identical.

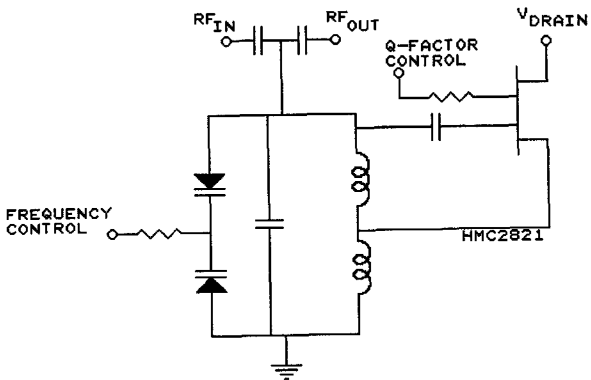

Figure 1. Basic topology of the active band-pass filter sections.

Figure 2 shows the basic topology for the series LC notch filter resonators. The negative resistance is generated in a fashion similar to that of the band-pass circuit, but using a single-gate FET. In this case, the negative resistance (Qu) control is implemented by adding a small amount of loss to the resonator through a second FET, which operates as a voltage-controlled resistor. To get higher-order notch responses (better skirt selectivity), two or more of these series-resonant circuits can be

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cascaded using quarter-wavelength line sections, as shown in Figure 3. The characteristic impedance Zo is chosen to obtain the desired notch bandwidth with realizable resonator element values, and suitable input/output matching circuits are used to obtain flat pass-band response.

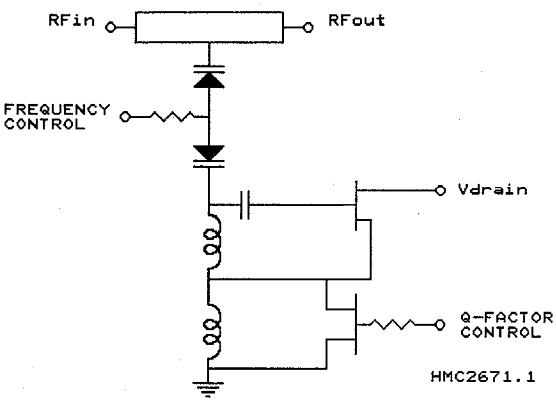

Figure 2. Basic topology of the active notch filter sections.

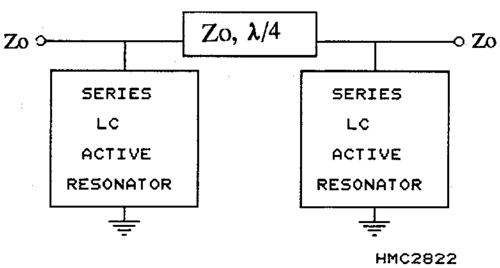

Figure 3. Two-section notch filter configuration.

We designed several notch filters circuits with a 6-18 GHz pass-band goal and a notch tuning range of about 2 GHz at X-band. Some variations of the Figure 2 resonator topology were used to increase power-handling performance and stabilize the notch bandwidth over the tuning range. Input matching was achieved through a broad-band, lumped-element, passive network. A single-stage, common-gate FET amplifier stage was used at the filter output to provide impedance matching, pass-band loss compensation, and the reverse isolation needed for unconditional stability.

FILTER CONTROL CIRCUIT

A master-slave filter control scheme is used to provide the optimum Q-factor and frequency control voltages for the MMIC filter resonators. Previously reported master-slave control circuits [8],[9] required separate master reference circuits for the frequency and Q-control loops. Our approach, illustrated in Figure 4, enables us to generate both control voltages using a single master active resonator cell designed with identical element values as those used in the filter sections in the slaved filter circuit. This master cell is isolated from any significant external losses so that it oscillates. A PLL circuit locks the oscillation frequency to that of a reference signal, and feeds the same frequency control voltage to the slaved filter resonators. The oscillation amplitude is limited by the gain (negative resistance) control loop to maintain the small-signal characteristics of its active device and tuning varactors. The resulting control voltage is exactly that required to cancel the losses in the master resonator at its oscillation frequency, resulting in an effective Qu of infinity. This is the same condition required for the slaved filter Q-control voltage to approximate the response of a filter with ideal, lossless resonators. However, the active filter response is not identical to that of an ideal passive circuit, mainly due to the inevitable mismatch between the frequency-dependence of the resonator losses and the FET-generated negative resistance.

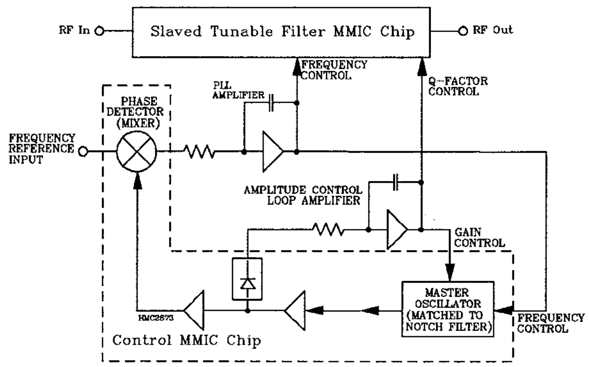

Figure 4. Basic block diagram of the master-slave control circuit.

All the rf components for the filter control circuits were integrated on a MMIC. Discrete op-amp ICs and passive components were used to implement the other control loop circuit elements.

MMIC FABRICATION

The active band-pass filter MMIC was fabricated with a 0.25 µm gate length MESFET process using epitaxially grown GaAs material. The notch filter MMICs were fabricated using a 0.5 µm gate length, ion-implanted devices. Via-hole grounds were used in both processes, and the varactors were implemented using MESFET structures with the same gate length as the active devices, by connecting their source and drain fingers together. Figures 5 shows a picture of the three-section band-pass filter chip and Figure 6 is a picture of a two-section notch filter chip, including its output amplifier stage.

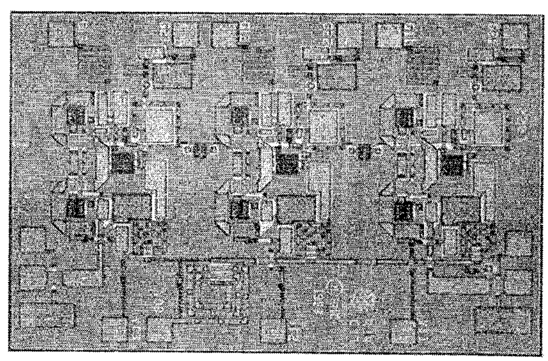

Figure 5. Photograph of a three-section band-pass filter, chip size is 1.3 x 2.0 mm².

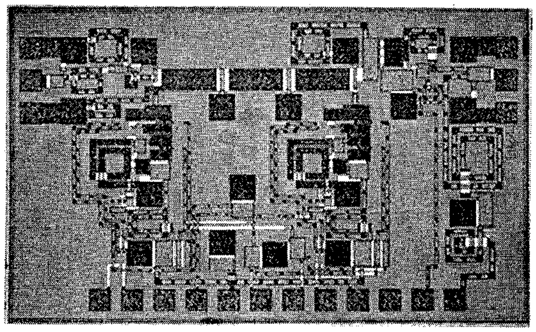

Figure 6. Photograph of a two-section notch filter with output buffer, chip size is 1.6 x 2.5 mm².

MEASURED PERFORMANCE

Figure 7 shows the measured chip-level response of the three-section band-pass active filter chip. It exhibits a minimum insertion loss of less than 1.5 dB, a -3 dB bandwidth of 0.23 GHz (3% of center-frequency), and an ultimate rejection greater than 49 dB. The total DC power dissipation of the chip is 0.3 W.

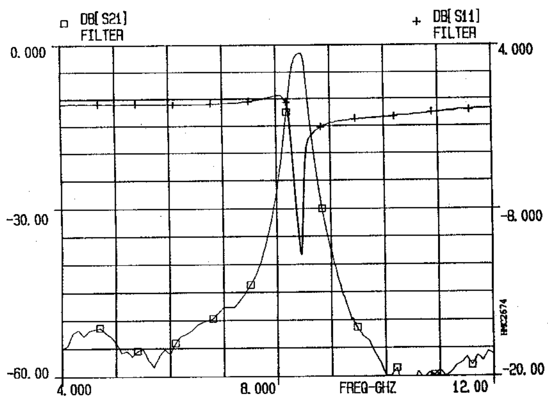

Figure 7. Measured transmission and reflection responses of the band-pass MMIC filter.

Figure 8 shows the transmission response of the two-section notch filter chip at two different notch frequency settings. The -30 dB notch bandwidths are 50 MHz and 20 MHz at the 9 and 11 GHz frequency settings, respectively. The -3 dB notch bandwidths are 0.21 and 0.17 GHz, respectively, at the same settings. In these measurements, the total DC power consumption of the chip is 0.34 W, of which 0.23 W is dissipated by the output amplifier stage. The notch frequency is tunable over a 2.7 GHz band, and the ± 2 dB ripple pass-band is 5.4 GHz to about 21.5 GHz.

Figure 9 shows the tracking performance of the control circuit/notch filter master-slave chip pair, measured in a test fixture, with the network analyzer sweeper signal coupled to the control circuit reference port. It can be seen that the control circuit could track the reference signal over a frequency range greater than 2.5 GHz, and the frequency and Q-factor control voltages that it applied to the slaved filter chip were accurate enough to maintain a notch depth greater than 25 dB over that band.

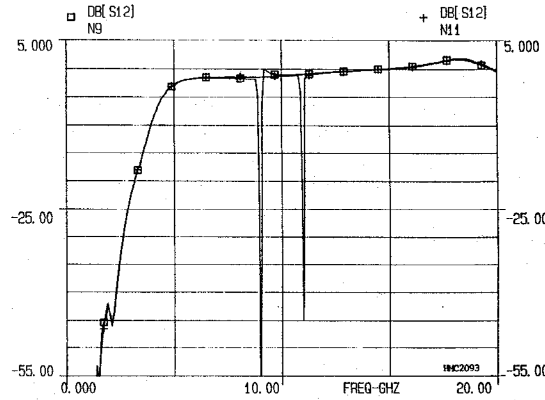

Figure 8. Measured transmission response of the notch filter MMIC at two different notch frequency settings.

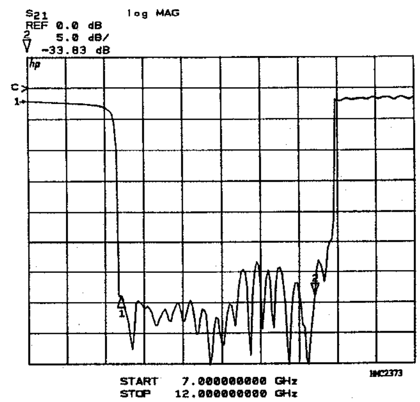

Figure 9. Measured tracking performance of the notch filter/master-slave control circuit combination.

Figure 10 shows the temperature compensation characteristics of the same control circuit. The high-temperature open-loop response was obtained by fixing the frequency and Q-control voltages to the same value as for the 29°C reference curve. From the high-temperature closed loop response curve, it can be seen that the control circuit virtually eliminates the temperature-induced notch depth variation, and it reduces the notch frequency drift to about one fifth of its open-loop value.

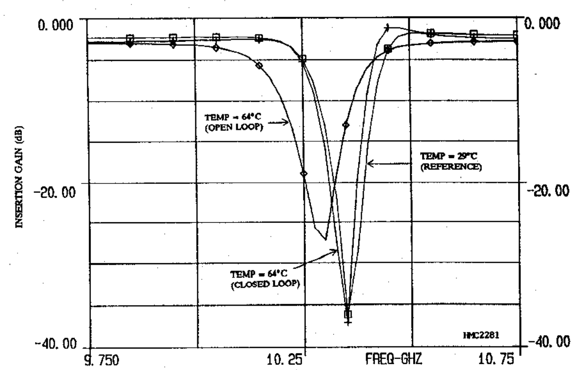

Figure 10. Measured performance of the notch filter over temperature with (closed loop) and without (open loop) the master-slave control circuit.

CONCLUSION

Fully integrated, narrow-band, tunable active filter MMICs have been demonstrated at X-band. The three-section band-pass chip had a minimum insertion loss less than 1.5 dB and a -3 dB bandwidth of 3% at 8.4 GHz. The notch filter chip exhibited a minimum -30 dB notch bandwidth of 20 MHz and a 2.7 GHz tuning range. A master-slave filter control circuit with fully integrated rf components was shown to track a reference signal over frequency range greater than 2.5 GHz while maintaining the slaved filter notch depth greater than 25 dB over that band. The same control circuit virtually eliminated the temperature dependance of the notch depth and provided a five-fold reduction in the notch frequency drift.

These results show that narrow-band, tunable microwave filters can be implemented at X-band using standard MMIC fabrication technology. Thus, this type of filter and control circuit designs could be combined with other functions to enable very compact integration of a wide range of rf systems.

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