RF on-chip LC passive bandpass filter based on GaAs MMIC technology

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The design and fabrication of a novel RF on-chip LC passive bandpass filter at S-band (2–4 GHz) based on using an LC passive lowpass filter and two DC-blocking capacitors are presented. The filter is accomplished with GaAs MMIC technology. Measurement results show that the quality factor (Q) of a 3 nH planar spiral MMIC inductor is 13.8 at 6.8 GHz and the self-resonant frequency is 15.5 GHz. The measured centre frequency of the bandpass filter shows agreement with the design performance and the contrast is 3.3%, the insertion loss of the filter is 6.7 dB at the centre frequency, and Q is 6.5.

Introduction: In monolithic microwave integrated circuits (MMIC), the RF filter is one of the most commonly used devices. At present, the filters applied in these circuits are bulky, expensive and off-chip discrete components, such as ceramic filters and surface acoustic wave (SAW) filters, etc. They not only occupy considerable space but also consume more power, which pose a primary bottleneck against the ultimate miniaturisation and integration of the system. The simplest approach to achieve on-chip filters is to employ on-chip inductors and capacitors. With the rapid development of RF integrated circuits and microelectromechanical system (MEMS) technology, it is fully possible to produce high performance on-chip inductors and capacitors [1, 2]. On-chip filters composed of inductors and capacitors are not only convenient and able to provide accurate regulation of fixed frequency circuits, but also greatly improve system integration and reduce production cost. Park and Allen [1] developed integrated LC passive filters composed of an air core spiral-type MEMS inductor with large suspension and a metal-insulator-metal (MIM) capacitor using thick copper electroplating and surface micromachining technology. Tsinghua University [2] developed the LC lowpass filter based on two MEMS inductors and a MIM capacitor using modified oxided porous silicon (OPS) technology, in which measured results gave a −3 dB bandwidth of 2.925 GHz and insertion loss of 0.874 dB at 500 MHz. However, the two filters utilised an abnormal process for obtaining high-quality on-chip inductors and capacitors, and even though both of them can be compatible with the traditional IC process they increase production cost. With the rapid development of semiconductor technology, the operation frequencies of RF and microwave circuits have reached several gigahertz, but the RF on-chip bandpass filter in the range 1–8 GHz has attracted less effective research owing to difficulty in fabricating a high-quality on-chip inductor and achieving much greater inductance.

This Letter presents the design and fabrication of a novel RF on-chip LC passive bandpass filter at S-band using an LC passive lowpass filter and two DC-blocking capacitors. It is achieved by on-chip planar inductors and on-chip capacitors, especially only needing fewer inductors and smaller inductance, and is completely compatible with GaAs MMIC technology. Measurement results show that the Q of a planar square MMIC inductor is 13.8 at 6.8 GHz and the self-resonant frequency is 15.5 GHz. The measured centre frequency of the bandpass filter is 3.1 GHz and shows agreement with the design performance ($f_0 =$ 3 GHz). The measured insertion loss of the filter is 6.7 dB at the centre frequency and the Q is 6.5. The filter can be applied to RF front-end circuits in the wireless system of the 1–8 GHz frequency range.

Design and fabrication: A challenging problem of designing on-chip LC passive filters focuses on accurately obtaining the desired inductance of MMIC inductors and capacitance of MIM capacitors. Moreover, when the inductors and capacitors operate in the RF range, various parasitic effects make inductance and capacitance deviate obviously from that of low frequency [3–6]. MMIC inductors and MIM capacitors presented in this Letter can greatly reduce parasitic losses at the RF range and improve the performance of on-chip filters. Recently, on-chip bandpass filters have been extensively required in the RF wireless system.The design of the RF on-chip LC passive bandpass filter is shown in Fig. 1. It should be noticed that the bandpass filter is not designed by the method of filter synthesis. In many cases, the transformation of a prototype lowpass to a bandpass filter needs not only a large number of inductors but also much more inductance, often reaching tens of nanohenries, whereas it is difficult for on-chip planar inductors to achieve such high inductance. Therefore, this Letter presents the simple π-network topology LC bandpass filter. In Fig. 1, C3 and C4 are DC-blocking capacitors, C1, C2 and L1 constitute a lowpass filter, and their cascade network can constitute a bandpass filter. Table 1 shows circuital and structural parameters of the bandpass filter.

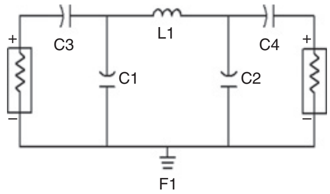


Fig. 1 *Circuit of RF on-chip LC passive bandpass filter*

Table 1: Circuital and structural parameters of RF on-chip LC passive bandpass filter

Type	Lumped elements and layout dimensions
Bandpass filter F1 Centre frequency 3 GHz	C1=C2=2.2 pF, L1=2 nH, C3=C4=1 pF
	L1 (layout): d_0 = 60 μm, w = s = 15 μm, n = 3.5
	C1 and C2 (layout): W = 37.5 μm, L = 100 μm
	C3 and C4 (layout): W = 20 μm, L = 75 μm

Note: d_0 is inner diameter of MMIC inductor, w is spiral metal width, s is spiral space, n is spiral turns; W is plate width of MIM capacitor, L is plate length

The RF on-chip LC passive bandpass filter was fabricated using the GaAs MMIC process with two-layer metal. The substrate material is GaAs and gold is used for constituting on-chip filters. The main process flow of a MMIC inductor is: (a) Au (0.3 μm) is sputtered on the GaAs substrate, and lithographed to form the underpass of the inductor; (b) SiN (0.1 μm) is deposited as the dielectric layer, and lithographed to form the connecting hole; (c) polyimide (1.6 μm) is deposited as the sacrificial layer; (d) Au (2 μm) is electroplated, and lithographed to form the inductor spiral winding; (e) the sacrificial layer of polyimide is removed using a developer. To fabricate the filters, integrated MIM capacitors consist of two parallel conductor plates (Au) separated by a high dielectric constant material (SiN).

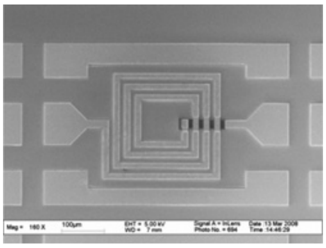


Fig. 2 *SEM photograph of MMIC inductor*

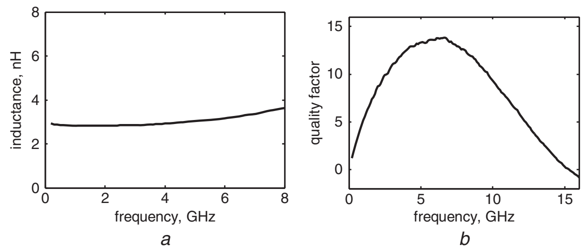


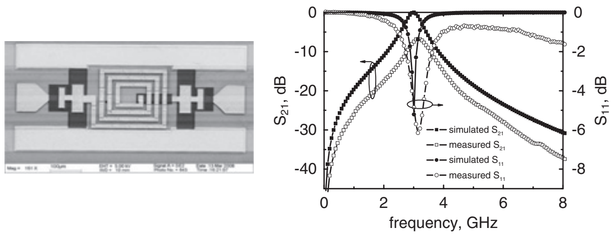
Fig. 3 *Measured inductance and quality factor of MMIC inductor*

a Inductance
b Quality factor

Measurement and analysis: S-parameters of MMIC inductors and on-chip filters were measured using a HP8510 network analyser and Cascade Microtech GSG probes. Parasitic effects of the pad of MMIC inductors are de-embedded from the measurement results using an open pad structure. Fig. 2 shows a SEM photograph of a MMIC inductor. Taking the layout dimensions of the inductor as an example, its inner diameter is 100 μm, the spiral metal width is 15 μm, the spiral space is

10 μm, and the spiral turn is 3.5. Fig. 3 shows the measured inductance and quality factor of the MMIC inductor. Measurement results show that the inductance is 3 nH from 0.5 to 4 GHz, the quality factor is 13.8 at 6.8 GHz, and the self-resonant frequency is 15.5 GHz.

Fig. 4 shows a SEM photograph and measured result of F1. F1 is a simple π-network topology bandpass filter, with centre frequency of 3 GHz. As shown in Fig. 4, the 50 Ω CPW transmission line is adopted by the on-chip filters and the G:S:G width of the CPW is 58 μm:100 μm:58 μm at ports. The size of the bandpass filter is $700 \times 400\ \mu m^2$. In Fig. 4*b*, the measured centre frequency of F1 is about 3.1 GHz, and the deviation compared with the design performance ($f_0 = 3$ GHz) is only 3.3%. The measured results also show that the −3 dB bandwidth is 0.47 GHz and the quality factor is 6.5. However, measured insertion loss is slightly high, at 6.7 dB, at the centre frequency of 3.1 GHz. The high insertion loss of F1 is caused by DC-blocking capacitors C3 and C4. The measured reflection loss of the bandpass filter is much larger compared with the simulated reflection loss, increasing to 2.26 dB at 2 GHz and reaching 4.79 dB at 4 GHz. Thus, the high insertion loss of F1 is also relevant to the impedance mismatch.



a b

Fig. 4 *SEM photograph and measured result of bandpass filter*

a SEM photograph
b Measured result

As can be seen through the measurement and comparison, the fabricated on-chip LC bandpass filter shows agreement with design parameters, and insertion losses are acceptable for applications. The deviations of measured and simulated results are inevitable. The main reasons include: the selected geometric dimensions of the MMIC inductor and MIM capacitors in the fabrication process are not accurate enough, which causes some deviations between inductance and capacitance values and design parameters; the on-chip inductor and capacitors embedded in the bandpass filter lead to mismatch with the 50 Ω CPW transmission line; various parasitic effects and numerous loss mechanisms of the RF on-chip inductor and capacitors have an impact on transmission characteristics of the filters. To reduce the impact of parasitic effects on the filters, selecting appropriate design margins in the parameters of centre frequency, passband loss and stopband rejection, etc., will make measurement results of the RF on-chip filter reach or approximate the design requirement. To reduce reflection losses, we can improve the gap size of the CPW transmission line and achieve the impedance match of the on-chip bandpass filter.

Conclusion: The design and fabrication of RF on-chip LC bandpass filters at S-band based on a LC passive lowpass filter and two DC-blocking capacitors are presented. It is accomplished with GaAs MMIC technology and occupies less chip area. The bandpass filter can be applied to RF front-end circuits in a wireless system operating in the 1–8 GHz frequency range. The design, fabrication and testing of the on-chip LC bandpass filter will be of important significance for achieving high performance RF on-chip filters.

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