Millimeter-Wave Active Bandpass Filters

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Abstract: *An exhaustive review of millimeter-wave (mm-wave) active bandpass filters (BPFs) is presented in this article. The details of various design approaches and realization techniques for the implementation of active BPFs are provided. The strengths, weaknesses, and design challenges of active BPFs are discussed. The available process technologies are investigated for the development of mm-wave filters. Active BPFs exhibit the merits of low loss, good out-of-band rejection, good selectivity, and a high integration level. By applying loss compensation techniques, active BPFs are realized with low losses. The aim of this paper is to motivate research and development of high performance mm-wave BPFs, especially above the 60 GHz frequency band.*

I. INTRODUCTION

The frequency range of the millimeter-wave (mm-wave) spectrum is from 30 GHz to 300 GHz. This spectrum offers various unlicensed frequency bands and supports the wireless communication in the range of gigabits/second (Gbps). Around 60 GHz, the unlicensed frequency bands of 57-64 GHz are available in USA and Korea, 59-66 GHz in Japan and Europe, 59.4-62.9 GHz in Australia, and 59-64 GHz in South Africa. Free-space path loss, mm-wave absorption by atmospheric oxygen and water vapour, rain attenuation, losses in building materials, and absorption by floors and walls affect and limit the mm-wave propagation. These effects make the 60 GHz band more suitable for short distance (less than 1 km) communications.

Electronic filters are used to allow the desirable frequency components and to reject the unwanted components of a signal. A bandpass filter (BPF) passes the frequencies within a specified range and attenuates other frequency components. A BPF is located between the antenna and the low noise amplifier (LNA) in the radio frequency (RF) receiver of a communication system.

BPFs can be divided into three types, including purely active, purely passive, and active (active + passive or semi-passive) [1]. In purely passive (passive) filters, only passive components, i.e., resistors, capacitors, and inductors are used. These filters do not have the capability of signal amplification. The power supply is not required for the operation of passive filters, therefore, they do not dissipate power. Since these filters do not consist of active devices, there is no active noise. They generate only thermal noise because of the resistive components. Consequently, passive filters demonstrate better noise performance. In purely active and active (semi-passive) filters, transistors are used as active components, therefore, these filters show the disadvantages of operating frequency limitations, poor linearity, high noise figure (NF), and power dissipation. These filters require smaller area than that of passive filters.

Passive filters suffer from the prime disadvantage of high loss. Active devices are used to compensate for the losses of passive resonators and to improve their quality factors (Q-factors). By applying loss compensation (Q-enhancement) techniques, active filters are realized and can be used in a transceiver module for reducing the loss and size [2]. Passive filters also have the shortcomings of incompatibility with tunable elements, trade-off between bandwidth (BW) and insertion loss (IL), and low out-of-band rejection levels. No complementary metal oxide semiconductor (CMOS) passive BPF with 3-dB fractional bandwidth (FBW) below 10% or above 65% has been reported.

On the other hand, CMOS active BPFs that have 3-dB FBWs less than 10% with low IL values are reported in [3], [4]. Since in active filter design, loss compensation techniques are used, the IL value can be reduced to 0-dB [3], [5], [6]. Moreover, good out-of-band rejection can be achieved using active filters at low as well as high frequencies. Besides the advantages of small size and low loss, active monolithic filters also have the qualities of good selectivity, a high level of integration with other circuits, and electronic tuning capability.

Traditionally, gallium arsenide (GaAs) and indium phosphide (InP) (III-V technologies) were assumed to be the only appropriate options for mm-wave circuit implementation because of the high speed device operation. III-V heterojunction bipolar transistor (HBT) and high electron mobility transistor (HEMT) technologies offer high cutoff frequencies (f_T). GaAs and InP substrates show semi-insulating characteristics, with high resistivity in the order of 10^7-10^9 Ω-cm. However, III-V technologies exhibit the drawbacks of low thermal conductivity (0.46 for GaAs and 0.68 for InP at 300K, while silicon (Si) has 1.41), high leakage current, device reliability issues, a low integration level, and high cost.

CMOS process demonstrates the merits of low cost, high integration level, and high reliability. MOS field effect transistor (MOSFET) scaling has supported to produce high speed transistors in CMOS technology. Nevertheless, low Q-factors of on-chip passives and poor noise performance are the major drawbacks of CMOS process. Besides CMOS, silicon germanium bipolar CMOS (SiGe BiCMOS) is another prominent Si technology used in RF and mm-wave circuit design. SiGe HBT offers higher gain and better noise and power performance than Si bipolar junction transistor (BJT). The performance of SiGe BiCMOS process is competitive with GaAs and InP processes. The actual strength of SiGe technology is to use CMOS process for the fabrication of digital, analog, and RF modules on a single chip. This ability is not available with any other technologies (GaAs, InP etc.).

II. ACTIVE BPF DESIGN APPROACHES

Various approaches to active BPF design have been reported, some of which include transversal, recursive, cascade connections of passive filters with amplifiers, active matching, active inverter, negative capacitance, and negative resistance. Among all these approaches, the negative resistance technique is the simplest and most appropriate for mm-wave active filter design [2]. This topology can be used in both lumped and distributed resonators. Negative resistance is used to increase the Q-factor of the passive network by resistive loss compensation. This approach makes active filters more stable, and they also exhibit a good rejection ratio [7]. The negative resistance topologies include transformer feedback, tapped-inductor feedback, active capacitance, active device reduction, cross-coupled pair, and others.

Fig. 1 illustrates a resonator made of a quarter-wavelength ($\lambda/4$) transmission line (TL). The short circuited port of the resonator is replaced with a negative resistance ($-R_N$) for the loss compensation of this resonator. The expression of loss as a function of attenuation constant (α) of the TL is represented by (1). Equation (2) expresses the gain generated by the negative resistance in terms of the line characteristic impedance (Z_0) and R_N. When (3) is satisfied, loss of the resonator is completely compensated, and its Q-factor becomes infinite. For this condition, R_N is represented by (4). If the value of R_N is greater than that provided by (4), the resonator holds a loop-gain, and oscillation arises [2].

$$\text{Loss} = e^{-\lambda\alpha/2} \tag{1}$$

$$\text{Gain} = \frac{-R_N - Z_0}{-R_N + Z_0} \tag{2}$$

$$\text{Loss} \times \text{Gain} = 1 \tag{3}$$

$$R_N = \frac{Z_0(e^{\lambda\alpha/2} - 1)}{e^{\lambda\alpha/2} + 1} \tag{4}$$

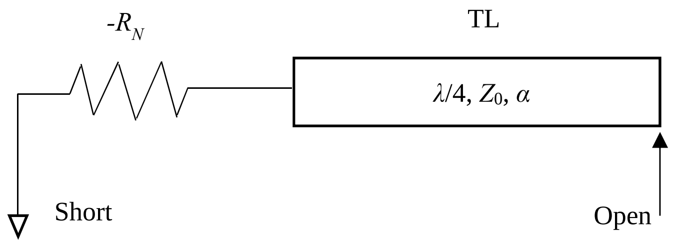

Fig. 1. Schematic for loss compensation through negative resistance [2].

Besides satisfying (4), negative resistance should be constant over a broad frequency range for compensating the loss of a passive resonator without causing oscillation and instability. Fig. 2 demonstrates the negative resistance circuit with an FET as an active component, and Fig. 3 shows the schematic of a two-stage active BPF using the negative resistance technique.

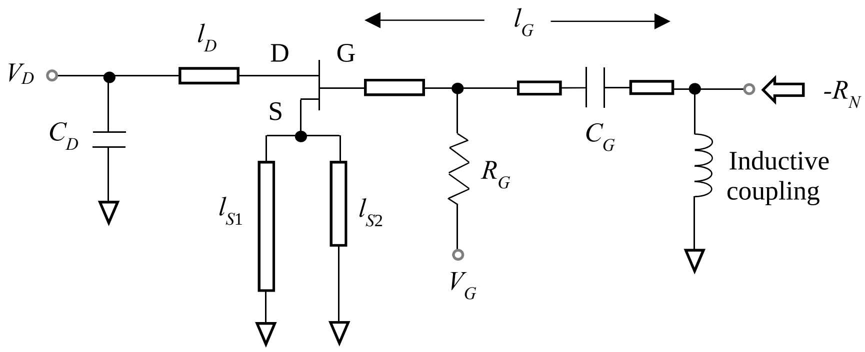

Fig. 2. Negative resistance circuit [2].

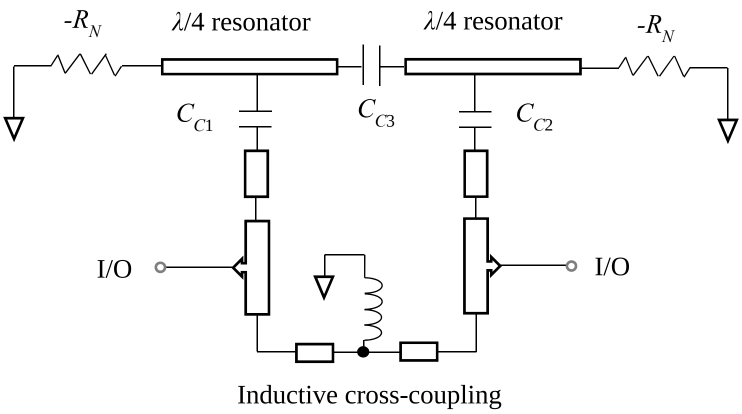

Fig. 3. Two-stage active BPF with negative resistance [2].

III. ACTIVE BPF REALIZATION TECHNIQUES

Active BPF realization can be broadly classified into two categories: Q-enhanced non-TL based and Q-enhanced TL based. The Q-enhanced non-TL based technique can be further divided into two parts: LC based and active capacitance based.

Q-enhanced LC based active BPFs mainly use transformer feedback [8], [9] and tapped-inductor feedback [10] architectures. The tapped-inductor feedback technique provides a high inductance value, low power dissipation, and small size compared to the conventional transformer feedback topology. Nonetheless, active BPFs realized with both of these topologies have the disadvantages of relatively high NF and power consumption. These topologies generally use common-source or common-gate series feedback structures, which are mostly employed in the oscillator circuit design. Owing to the series feedback structure, the noise performance of active BPFs is degraded [1].

In low GHz (less than 10 GHz) RF integrated circuit (IC) design, the main challenge is the low *Q*-factors of on-chip passive inductors. The IL of active BPFs at these frequencies is mostly governed by the low-*Q* of these inductors. In mm-wave frequency band, passive inductors show desirable *Q*-factors of 15 or more. The *Q*-factors of on-chip passive inductors increase with increasing frequencies, while those of on-chip passive capacitors tend to decrease. Therefore, in mm-wave filters, the IL is mainly affected by the *Q*-factors of capacitors. The NF also depends on the IL value, so the IL and NF can both be reduced by using high-*Q* capacitors in active filter design [11]. Furthermore, with increasing frequencies, the capacitance values of on-chip passive capacitors also increase. The low *Q*-factors and deviation in capacitance values with frequencies are serious drawbacks of these capacitors. Consequently, the overall performance of mm-wave ICs is significantly degraded. On-chip active capacitors are a better substitute for on-chip passive capacitors. Active capacitors are constructed with transistors and possess high *Q*-factors and tunable capabilities. These high-*Q* capacitors can be used for loss and noise performance improvement of mm-wave active BPFs. *Q*-enhanced LC based active BPFs suffer from poor noise and power performance, but the BPFs realized with the active capacitance technique do not have such types of demerits. BPF design with the active capacitance method for resistive loss compensation is reported in [1], [11].

Active BPFs are proposed using *Q*-enhanced TL based techniques, such as cross-coupled pair [3]-[5], [12] and coupled negative resistance [13]. Different cross-coupled pair architectures are applied to the resonator to compensate for the resistive losses, including nMOS cross-coupled pair [5], [12], [14] and complementary cross-coupled pair [3], [4]. The realization of passive resonators by using synthetic quasi-transverse electromagnetic (quasi-TEM) TLs, also known as complementary conducting strip TLs (CCS TLs), is reported in [3], [4]. Compared to the conventional thin-film microstrip line, CCS TL can provide more parameters for the guiding characteristics synthesis without any change in the process and material constants. In addition, CCS TL can be meandered in the 2-D plane with fewer coupling effects. Efficiently meandered CCS TL can provide compact layout, size miniaturization, and a high degree of integration. All these attractive features of CCS TL support its application in monolithic microwave integrated circuits (MMICs) and system on chip (SOC) implementation. A modified form of CCS TL, known as condensed complementary conducting strip TL (C-CCS TL) is proposed in [12] for passive resonator realization. C-CCS TL has a great capability of further area reduction. Both the CCS TL and C-CCS TL facilitate size minimization and *Q*-factor improvement simultaneously and can, therefore, be selected for TL based compact mm-wave BPF design.

IV. SELECTIVITY AND MULTIMODE

The selectivity of low order on-chip BPFs is unsatisfactory [10]. Conventional second-order BPFs show low out-of-band rejection levels. The selectivity of a filter can be improved by increasing the order, but it also increases the IL and chip area. Various highly selective active BPFs are reported by using the concept of transmission zeros. These transmission zeros are placed on both sides of their passband.

Most of the on-chip BPFs have been designed using singlemode resonators. The size and loss of a filter can be reduced by modifying the conventional resonator to generate additional modes for the realization of multimode operation [15]. SiGe BiCMOS on-chip multimode passive

BPF based on multimode resonator (MMR) is proposed in [15]. This designed multimode BPF displays low IL with a small chip area. Dualmode BPFs have achieved great importance in advanced wireless communication systems because of their high *Q*-factor, good selectivity, and narrowband performance. Dualmode active BPF was first reported in [16]. A ring resonator based dualmode CMOS active BPF using CCS TLs is presented in [3].

V. PERFORMANCE COMPARISON

The performance parameters of previously reported active BPFs are compared in [1], [3], [5], [8], [10], [17]. Table 1 presents the performance summary of various active BPFs.

Table 1. Performance comparison of active BPFs.

Ref.	Process	N	f_c (GHz)	3-dB BW (%)	P_{DC} (mW)	NF (dB)	P_{1dB} (dBm)	Chip area (mm^2)	IL (dB)	RL (dB)	FOM (dB)
[8]	0.18 μm CMOS	4	2.03	6.5	16.6	15	-6.6	1.21	0	10	77
[6]	0.25 μm CMOS	3	2.14	2.8	17.5	18.9	-13.4	3.51	0	12	68.9
[9]	0.18 μm CMOS	3	2.36	2.53	8.8	19	-20	2.25	1.8	11.5	66
[7]	0.15 μm GaAs	2	22.6	4	50.4	17	-19	1	8	7.7	67.5
[5]	0.18 μm CMOS	2	34.2	18.8	3.7	7*	-4.6	0.12**	0	14.6	98.3
[4]	0.18 μm CMOS	2	22.7	7.39	3.3	14.05	-7.7	0.13**	0.15	9.96	91
[10]	0.18 μm CMOS	2	23.5	17	4.2	6.7	-3.5	0.37	1.65	13.2	98
[17]	0.18 μm CMOS	2	2.44	2.46	10.8	18	-15	0.53	6	19	70
[14]	0.18 μm CMOS	2	6.02	18.94	5.4	12	-15.2	1.08	2.2	7.64	73.5
[12]	0.18 μm CMOS	3	1.58	8.0	14.4	15	-13.83	0.92	0.68	16	67.6
[3]	0.13 μm CMOS	2	24.1	3.86	5.4	14.05	-25.43	0.073**	0	13.3	74
[1]	0.18 μm CMOS	2	5.3	32	2.2	4.3	2.5	0.7	0.77	18	100
[2]	0.15 μm GaAs	2	65	4	-	10.5	-	2.75	3	9.4	-
[2]	0.15 μm GaAs	2	65	2	-	-	5	2.75	2.8	9.1	-

* Simulated results

** Without testing pads

N, f_c, P_{DC}, P_{1dB}, and RL are the order (number of poles), center frequency, DC power dissipation, in-band input 1-dB compression point, and return loss, respectively, of a BPF.

Figure of merit (FOM) is a parameter used to compare active RF BPFs and is defined as follows [8], [10]:

$$\mathrm{FOM_{dB}} = 10\log\left(\frac{N \times \mathrm{P_{1dB}} \times f_c}{\mathrm{FBW} \times \mathrm{P_{DC}} \times \mathrm{NF}}\right) \qquad (5)$$

where P_{DC} and P_{1dB} are in W, f_c is in Hz, and NF and FBW are actual values (not converted to dB and percentage, respectively). The FOM value has been provided for the filters listed in Table 1.

VI. WEAKNESSES OF ACTIVE BPFs

There are some weaknesses of active filters, such as high NF, operating frequency limitations, and their sensitivity to process variations and environmental conditions. Very few active BPFs are implemented in mm-wave frequency band, i.e., the filters that have center frequencies beyond 30 GHz. The center frequencies of these reported mm-wave BPFs include 31.8 GHz in GaAs process [18], 34.2 GHz in CMOS process [5], 40 GHz in CMOS process [11], and 65 GHz in GaAs process [2]. Reducing the NF and increasing the operating frequency of active BPFs are major design challenges.

VII. CONCLUSION

This paper provides a detailed review of mm-wave active BPFs. On-chip active BPFs have the main disadvantages of high NF and moderate operating frequency. To the best of the authors' knowledge, only one research article (published in 2004) has reported active BPFs with center frequencies around and above 60 GHz, and these filters are implemented in GaAs process. The performance and feasibility of CMOS process for the design of such high frequency active filters need to be investigated. CMOS RF circuits face the problem of poor noise performance. SiGe BiCMOS process may be an appropriate alternative.

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