Millimeter-Wave Passive Bandpass Filters

Saurabh Chaturvedi, Mladen Božanić, and Saurabh Sinha

Department of Electrical and Electronic Engineering Science, Faculty of Engineering and the Built Environment
University of Johannesburg, Auckland Park Kingsway Campus
Johannesburg, South Africa
E-mail: chaturvedi.s.in@ieee.org, mbozanic@ieee.org, ssinha@ieee.org

Abstract: *This paper presents a comprehensive review of millimeter-wave (mm-wave) passive bandpass filters (BPFs). A detailed discussion is provided on different topologies and architectures, performance comparison, design challenges, and process technologies. Passive BPFs offer the advantages of high operating frequency, good linearity, low noise figure (NF), and no power dissipation. Careful consideration of available process technologies is required for the implementation of high performance mm-wave circuits. Gallium arsenide (GaAs) and indium phosphide (InP) (group III-V) processes provide high cutoff frequencies (f_T), good noise performance, and high quality on-chip passives. Complementary metal oxide semiconductor (CMOS) process has the prominent advantages of low cost, a high degree of integration, and high reliability, while silicon germanium bipolar CMOS (SiGe BiCMOS) process demonstrates high f_T, a high level of integration, and better noise and power performance.*

Keywords: Bandpass filter (BPF), millimeter-wave (mm-wave), transmission line (TL), lumped element, conductive substrate, CMOS.

I. INTRODUCTION

The millimeter-wave (mm-wave) band of the electromagnetic (EM) spectrum spans from 30 GHz to 300 GHz. The free space wavelength for this spectrum is in the mm range (1-10 mm). World-wide availability of unlicensed frequency bands around 60 GHz makes the mm-wave band very attractive for high speed wireless data transfer at multi-gigabits/second (Gbps) [1]. The operating frequencies of wireless communication systems have increased rapidly with the continuous growth in communication technology. Owing to the development of mm-wave transceivers, high speed data transfer through wireless local area networks, wireless home networks, and wireless personal area networks is possible.

In these communication systems, filters are essential front-end components for signal selection at specific frequencies. Their electrical responses are critical for the overall system performance. A bandpass filter (BPF) allows in-band signals and sufficiently rejects unwanted out-of-band signals. In a radio frequency (RF) receiver, a BPF is situated between the antenna and the low noise amplifier (LNA), as shown in Fig. 1.

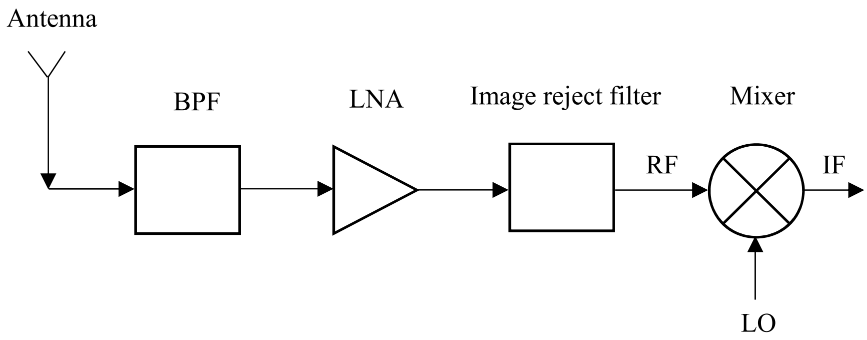

Fig. 1. BPF in RF receiver.

A BPF of small size, with a high quality factor (Q-factor), low noise figure (NF), low insertion loss (IL), high return loss (RL), good selectivity, and high out-of-band rejection (stopband rejection) is required to improve the performance of an RF receiver. In general, systems can be divided into two categories: system on chip (SOC) and system on package (SOP). In SOC, all the functions of a complete system, including digital, analog, RF, and others, are implemented in a single integrated circuit (IC). SOP, a system-level package, contains multiple ICs for the realization of entire functionality of the system. In the mm-wave spectrum, monolithic ICs are preferred over hybrid ICs because of cost, size, reliability, reproducibility, design flexibility, and level of integration issues. Off-chip BPFs are not suitable for modern high speed wireless transceivers because they are bulky and expensive. Removing off-chip components reduces the size and cost of a system. Therefore, the development of new design techniques for on-chip implementation of the components previously designed off-chip is a major driving force for advanced communication systems [2].

BPFs can be classified into three categories: purely active, purely passive, and active (active + passive or semi-passive) [3]. The advantage of purely active BPFs is small size, but their operating frequencies are low, and they also suffer from poor linearity, high NF, and high power dissipation. Purely passive BPFs can be operated at high frequencies, have good linearity, low NF, and zero power dissipation but require a large silicon (Si) area. The characteristics of active BPFs are medium operating frequencies, poor linearity, high NF, medium power dissipation, and a smaller area than that of passive filters. Table 1 summarizes the features of all three BPF types.

Table 1. Comparison of characteristics of BPFs [3].

Filter type	Operating frequency	Linearity	Noise figure	Power dissipation	Area
Purely active	Low	Poor	High	High	Small
Purely passive	High	Good	Low	Zero	Large
Active (active + passive)	Medium	Poor	High	Medium	Large, but smaller than passive

The manufacturing technologies commonly used for RF filters include monolithic microwave integrated circuit (MMIC), low temperature co-fired ceramic (LTCC), and printed circuit board

(PCB). Various process technologies are used for the fabrication of filters, including Si microelectromechanical systems (Si MEMS), gallium arsenide (GaAs), GaAs MEMS, Si benzocyclobutene (Si BCB), Si germanium (SiGe), integrated passive device (IPD), liquid crystal polymer (LCP), and complementary metal oxide semiconductor (CMOS).

GaAs and indium phosphide (InP) (III-V technologies) processes demonstrate better performance than CMOS process because of a higher breakdown voltage, higher electron mobility, and high quality passives [4]. These processes offer high cutoff frequencies (f_T) and good noise performance. However, high cost, a low level of integration, and high power dissipation are the major drawbacks of III-V semiconductor technologies. Low cost, a high integration density, simple fabrication steps, scaling capability, and good reliability are the main advantages of CMOS process through which digital, analog, and RF modules could be integrated in a single chip. Continuous scaling of CMOS technology has produced MOS transistors that have cutoff frequencies beyond 100 GHz. With the MOS field effect transistor (MOSFET) scaling, the f_T and the maximum oscillation frequency (f_{max}) are both increased. Scaling improves the speed and noise performance of MOS transistors.

Because of the low resistivity of Si substrate, typically 10 Ω-cm used in mm-wave circuits, the on-chip passive components exhibit low *Q*-factors and suffer from high losses in CMOS process. Substrate and metal losses are the severe issues of CMOS process. In addition, polysilicon is used as the gate material in CMOS devices. The sheet resistance of polysilicon (approx. 10 Ω/□) is much higher than that of metal, which consequently increases the MOSFET gate resistance. The high gate resistance can decrease the power gain of a MOSFET and increase noise. Noise is a severe problem in CMOS RF circuit design. By using layout techniques, these effects of the polysilicon gate can be reduced [4]. All the factors mentioned cause degraded frequency responses of BPFs, such as IL, RL, and out-of-band rejection. Similar to CMOS process, SiGe bipolar CMOS (BiCMOS) process also provides high f_T and f_{max}. In addition, SiGe heterojunction bipolar transistors (HBTs) display superior noise performance and better transconductance. SiGe BiCMOS process is the most suitable contender for low noise, low power, high density, and low cost RF circuit design.

II. TRANSMISSION LINES AND LUMPED ELEMENTS

At mm-wave band, the size of a passive filter gets smaller than that of a filter at microwave frequency band. This supports the integration of an mm-wave passive filter with other circuits on a single chip and helps in developing the miniaturized system at lower cost [5].

The *Q*-factor of a monolithic transmission line (TL) is directly proportional to the square root of the frequency of operation. Thus, with increasing frequencies, the *Q*-factor of a TL is enhanced. Consequently, TLs are broadly used and preferred as resonators for mm-wave passive filter design [6]. Below 30 GHz frequency, passive filters based on lumped circuit elements are more compact than the filters realized with TLs. Above 30 GHz, lumped elements filters' implementation demands exact models and manufacturing techniques with high precision. Around and over 60 GHz frequency, TL based implementation is more suitable and has high potential for monolithic passive filter design [7].

At mm-wave frequency band, the reactive elements required for matching networks and resonators get very small, and need inductance values in the range of 50-250 pH. Quasitransverse electromagnetic (quasi-TEM) TLs are easily scalable in length and can realize small reactances. In addition, the modeling of TL based interconnects is simple. Another advantage with TLs is that the well-defined ground return path reduces electric and magnetic field coupling to adjoining structures [4]. Fig. 2 shows the distributed circuit model for the quasi-TEM TL. This TL can be characterized by using (1)-(4).

$$Z_0 = \sqrt{\frac{L}{C}} \quad (1)$$

$$\lambda = \frac{2\pi}{\omega_0 \sqrt{LC}} \quad (2)$$

$$Q_L = \frac{\omega_0 L}{R} \quad (3)$$

$$Q_C = \frac{\omega_0 C}{G} \quad (4)$$

R, *L*, *G*, and *C* are the resistance, inductance, conductance, and capacitance per unit length, respectively. Z_0 and λ are the characteristic impedance and signal wavelength for a lossless ($R = G = 0$) TL. ω_0 is the resonant angular frequency, Q_L is the inductive quality factor, and Q_C is the capacitive quality factor. TLs on conductive Si substrate have low values of Q_C because of the effect of substrate coupling. Q_L is the most crucial parameter for determining the TL loss.

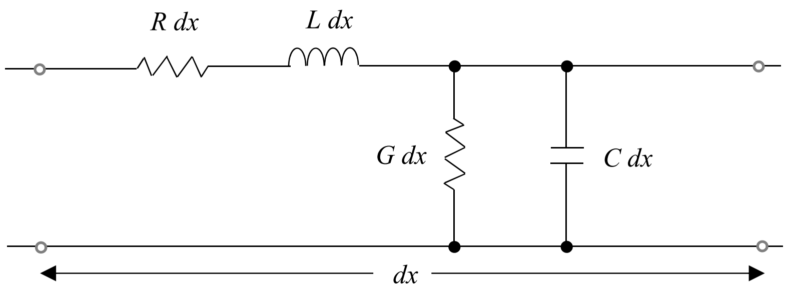

Fig. 2. Distributed quasi-TEM TL model [4].

In recent years, many efforts have been made to implement mm-wave lumped passive filters. A number of integrated miniature mm-wave lumped BPFs are available in literature. BPFs with spiral inductors and metal-insulator-metal (MIM) capacitors are realized in [8], [9]. BPF design using interdigital capacitors is reported in [10]. For the realization of very small capacitance values, interdigital capacitors are preferred. Compared to interdigital capacitors, MIM capacitors have lower *Q*-factors owing to high dielectric losses at mm-wave frequencies. Since the filters with interdigital capacitors do not involve MIM processing, the process cost can be significantly reduced. Nonetheless, the area of an MIM capacitor is much smaller. Because of the larger size of an interdigital capacitor, associated parasitic inductances are increased and affect the device performance [10]. Table 2 summarizes the comparison between the MIM capacitor and interdigital capacitor.

Table 2. Comparison between MIM and interdigital capacitors.

Feature	MIM capacitor	Interdigital capacitor
Q-factor	Low	High
Process steps	More	Less
Cost	High	Low
Area	Small	Large

III. PASSIVE BPF TOPOLOGIES

The topologies of mm-wave passive BPFs reported in literature include coupled-line [2], [11], ring resonator [12], [13], and stepped impedance resonator [14], [15]. The planar π-filter configuration has shown the advantage of bandwidth (BW) insensitivity to the layout and substrate thickness variations on different processes, such as PCB [16], GaAs substrate [17], and Si substrate [18]. Therefore, this configuration displays a larger design margin. However, there are two drawbacks to the planar π-filter structure: a relatively large area and difficulty in SOC integration. These disadvantages can be avoided by using compact microstrip line (MSL) inductors [9]. Fig. 3 presents the schematic of a CMOS passive BPF with planar π-filter configuration. Miniature on-chip MIM capacitors and MSL inductors are used for realizing the miniaturized BPF.

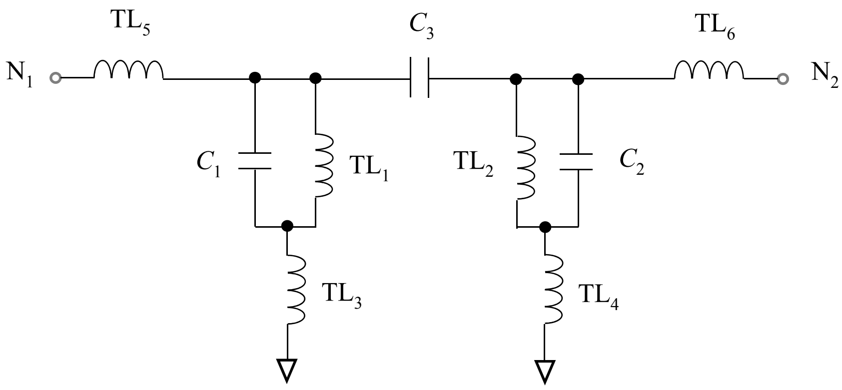

Fig. 3. Schematic of miniaturized passive BPF [9].

IV. PERFORMANCE COMPARISON

The performance parameters of previously published passive BPFs are compared in [2], [6], [9], [10], [19]-[21]. Table 3 demonstrates the performance summary of various mm-wave passive BPFs.

Table 3. Performance comparison of mm-wave passive BPFs.

Ref.	Process and technology	f_c (GHz)	3-dB BW (%)	IL (dB)	Chip area (mm^2)
[22]	Si MEMS	60	8.0	1.5	22.8
[22]	Si MEMS	60	2.7	2.8	22.0
[22]	Si MEMS	60	4.3	3.4	26.0
[23]	Si BCB	50	5.0	4.6	12.2
[23]	Si BCB	94	5.0	7.0	3.9
[24]	LTCC	60	3.5	4.0	6.3
[25]	LTCC	60	4.1	2.8	4.0
[8]	SiGe	77	15.5	6.4	0.01
[2]	0.18 μm CMOS	60	10.0	9.3	0.14
[2]	0.18 μm CMOS	77	10.0	9.3	0.11
[12]	0.18 μm CMOS	64	18.75	4.9	1.71
[9]	0.13 μm CMOS	60	18.28	2.55	0.085
[14]	0.18 μm CMOS	66	18.05	3.1	0.074
[14]	0.18 μm CMOS	61	18.03	3.5	0.074
[26]	GaAs	58	15.0	3.4	4.0
[27]	IPD	62	19.35	2.3	0.49
[28]	IPD	77	8.3	2.46	3.36
[29]	LCP	65	12.3	3.0	4.88

f_c is the center frequency of a BPF. 3-dB BW (%), also known as 3-dB fractional bandwidth (FBW), is defined by (5).

$$\text{3-dB BW (\%)} = \frac{\text{BW}}{f_c} \times 100 \qquad (5)$$

V. WEAKNESSES OF PASSIVE BPFs

Passive filters have a significant drawback of high loss. The *Q*-factor of a passive resonator is degraded owing to the ohmic (metal), dielectric, and radiation losses. The bulky structure of passive waveguide filters increases the size of the fully integrated transceiver module. Passive planar filters are small in size but suffer from losses.

Other critical drawbacks associated with passive filters include incompatibility with tunable elements and trade-off between BW and IL. Various limitations and design challenges of mm-wave passive BPFs in CMOS process are analyzed and explained in [21]. In literature, no CMOS passive filter has been reported with 3-dB FBW below 10% or above 65%. Filters with FBWs below 20% experience high losses. Therefore, the realization of such narrowband passive BPFs with low IL is a crucial design challenge. Another design challenge is to implement passive filters with high out-of-band rejection levels.

VI. CONCLUSION

A review of mm-wave passive BPFs is presented in this article. The paper discusses the merits, demerits, design techniques, topologies, and design challenges of these filters. The salient shortcomings of on-chip passive BPFs include high loss and trade-off between BW and IL. Various process technologies for the implementation of mm-wave filters are discussed and compared in detail. This review article will help researchers to identify the research gaps and also motivate them to undertake future development in the area of mm-wave filter design.

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