High-Tc Superconducting Microwave and Millimeter Devices and Circuits—An Overview

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ABSTRACT

High temperature (high-Tc) superconductors (HTS) have found many applications in the last two decades. To microwave researchers and engineers, the ultra-low surface resistance of the thin-film HTS materials at microwave and millimeter frequencies and the highly non-linear Josephson junctions are of particular interest. The former can be exploited in the design and fabrication of passive microwave components and circuits with superior performance, and the latter can be exploited to create many novel active HTS devices. This paper provides an overview of the state-of-art development of HTS devices and circuits for microwave and mm-wave communication front-end receiver systems. The paper is particularly focused on the latest advancement of HTS Josephson junction based active devices, monolithic microwave integrated circuits (MMIC), and whole receiver systems integrated with cryocoolers.

INDEX TERMS Filters, high temperature superconductors (HTS), Josephson junction, mixers, receivers.

I. INTRODUCTION

Since the discovery of high-Tc superconductor (HTS) with transition temperature (Tc) above liquid-nitrogen temperature in 1987, enormous progress has been made to improve the HTS material property and develop various practical applications. HTS materials have distinctive advantages over the conventional low-temperature superconductors (LTS) materials due to their significantly higher superconducting transition temperatures. The HTS systems can be cooled in inexpensive liquid nitrogen or small cost-efficient cryocoolers, making them far more attractive for practical applications and more likely to be adopted by industry. Research in HTS materials have seen continuous improvement in critical temperatures, critical current densities, and critical magnetic fields. This has facilitated research in multidisciplinary fields [1], [2], including power transmission cables, motors, generators, fault current limiters, superconductor magnetic energy storage systems (SMEs) [3], [4], magnetic resonance imaging (MRI) [5], electronic devices spanning wide electromagnetic spectra from DC to microwave, terahertz, and to optic regions [6]–[12].

The HTS technology has great potential to lead to major performance breakthrough in microwave and millimeter wave (mm-wave) components and subsystems for fast growing wireless communication, sensing and space industries. The surface resistance of HTS material is about 100-1000 times less than conventional metals such as copper and silver at microwave frequencies, and therefore they are the ideal materials to develop microwave filters with ultra-high performance, typically low insertion loss, narrow bandwidth, high stopband rejection, and steep skirt slopes. Research and developments on HTS filters dated back to the 1990s [13], and various types of high-performance HTS filters have been constantly reported. Low-loss, high-Q and flat-group-delay filters were developed for microwave and mm-wave receivers in wireless communication and radar applications [14]–[16]. Modern and future wireless systems have raised more stringent requirements to the filter performance in power handling and frequency agility, and novel HTS filters have also been developed to meet the challenges [17], [18].

Another very important property of HTS materials is related to low-noise Josephson junctions made from HTS thin films. The junctions’ extreme nonlinearity of the current-voltage (I-V) relationship is highly attractive for applications in active microwave devices, such as oscillators, amplifiers and mixers. Such superconducting active devices feature
extremely low noise, broad band and high frequency operation, and low power consumption. Research on HTS active devices commenced just after the discovery of HTS materials, resulting in the early development of HTS oscillators and mixers [7], [19]–[22]. Novel HTS active devices have been developed in recent years, based on a loop structure consisting of a pair of Josephson junctions interrupted with a resistor [23], [24], which functioned as a heterodyne current or voltage-controlled oscillator (VCO) and frequency mixer simultaneously across a wide frequency range.

HTS devices are typically operated between 40 – 77 K, which can be reached by a commercial single portable cryocooler. Therefore, implementation of superconducting electronic devices in HTS technology, instead of the low temperature superconductor (LTS) technology (operating below 10K) offers the potential to use cheaper and more compact cooling systems. HTS filters were integrated with mini-cryocoolers first in the late 90s [25], and the Josephson devices were successfully operated in a commercial cooler in 2005 [26], respectively. In 2014, a portable HTS Josephson frequency down-converter operating on a commercial mini cryocooler was demonstrated [27]. This HTS Josephson microwave circuit was operated successfully in the mini cryocooler unshielded, which demonstrated the potential of a portable all-HTS receiver front-end for application in wireless communications.

The HTS devices have been successfully deployed in the receivers for various wireless systems, including mobile communications, space communications and radar systems. HTS receivers have much better sensitivity and selectivity compared with conventional room-temperature base-station receivers, which leads to better communication quality and increased radio coverage. HTS receiver front-end subsystems developed by Superconductor Technologies Inc (STI) in the USA, which integrate narrowband highly selective HTS filters and a semiconductor low noise amplifiers (LNA) in a cryocooler, have been widely applied in over 10,000 base stations [28]. According to STI, the ultra-low-loss and high sensitivity of the HTS receiver can translate into a 10%–15% or more increased base station coverage area and data throughput. In 2010, an HTS transceiver for TD-SCDMA was developed [29], and field trials were carried out in a commercial network by replacing the conventional transceiver with a HTS receiver. Measurement results showed significant improvements in bit-error-rate and anti-interference capability, which result in higher quality of video communications.

HTS receivers for space applications have also been investigated and developed worldwide [30]–[38] or have carried out on-orbit measurements. In [30], it was reported that HTS materials and devices were also extremely radiation hard, generally several orders of magnitude harder than semiconductor materials and devices. HTS electronic components can be used in satellite communications and surveillance systems, for both military and civilian applications.

The high selectivity of HTS filters is a character highly desired in radar systems to eliminate the interference frequencies. A multichannel superconducting front-end T/R module was reported in [39], [40], with HTS filters integrated with LNAs in each channel. The HTS filter was designed to have a compact size so that all the 16 cryogenic circuits are contained within one vacuum chamber and cooled by a small cooler. Besides the low noise figure (noise temperature less than 60 K), the HTS sub-array modules also showed other excellent performance characteristics, such as low amplitude deviation and good phase linearity. These HTS receiver systems, however, have not included HTS Josephson junction active devices because of very challenging HTS Josephson junction technology.

Apart from scientific research, great efforts have been made by the HTS industry for the production of HTS microwave/mm-wave devices and systems. Customized cryogenic systems can be sourced from a number of commercial companies, such as Cryoelectra and Cosmic Microwave Technology, Inc. Other companies that provide cryogenic components and system solutions include HYPRES, Thales, and Atlantic Microwave etc [41]–[45]. In particular, Cryoelectra developed HTS filters and cryogenic LNAs as front ends for mobile communication base stations between 1998 and 2003 in cooperation with Ericsson and Tsinghua University [41].

In 1990s and early 2000, major HTS microwave research efforts and achievements were made on passive circuits, and little progress was made in active devices and especially MMIC (monolithic microwave integrated circuit) due to very challenging and immaturity of HTS JJ technologies. Despite the superior performance of HTS filters, the high cost-to-value limited the widespread adoption of cryocooled HTS-filters in the receiver systems. The full benefit of HTS circuits cannot be realized if only HTS filters are implemented in the receiver systems. An all-HTS circuit with HTS passive and active components integrated monolithically would greatly improve the receiver performance due to more efficient signal coupling, the low loss of HTS transmission lines, and low noise of Josephson junctions. Additionally, Josephson mixers feature low power consumption due to the low DC biasing current at μA level, and low LO powers requirement (microwatt level), which, together with more compact size, would greatly reduce the overall power consumption of the cryogenic receiver front-ends. This is the motivation behind our research on HTS active devices and MMIC receivers. Early efforts were made in 1990s and early 2000s on the monolithic integration of HTS passive and active devices [46], [47], while major progress has been made by the authors’ group in developing HTS MMIC mixers with high conversion gain at microwave and mm-wave frequencies in recent years [48]–[50]. Theoretical investigations and new modelling methods of the HTS MMIC mixers have been developed to guide the design and optimization of the HTS MMIC mixer performances [51], [52].

In the rest of this paper, we provide a brief introduction of the HTS materials, Josephson junction technology, and fundamentals of the receiver systems in Section II, which are the bases of the HTS microwave technology. We then review the progress in the development of HTS passive devices
II. LOW SURFACE RESISTANCE, JOSEPHSON JUNCTION AND RECEIVER SYSTEMS

HTS materials feature exceptional low-loss performance in microwave frequency range. Fig. 1 shows the frequency dependence of the surface resistance, $R_s$, for YBa$_2$Cu$_3$O$_{7-x}$ (YBCO) (the most used HTS material) at 77K compared with that of a normal metal such as copper and a low-Tc superconductor (LTS) material Nb at 7K [53]. The surface resistance of HTS thin films, for example YBCO is one hundred times lower than that of copper at 10 GHz and at 77 K. Low value of surface resistance enables a high quality-factor (Q-factor) of a planar resonant structure – very narrow frequency response and highly accurate definition of resonant frequencies. These high-Q circuits are the key elements to develop high-performance filters featuring low-loss and ultra-narrow band to eliminate noisy signals or to separate two signals which are close together in frequency.

HTS Josephson junction consists of two weakly coupled superconducting electrodes, and it displays extraordinary behaviors under certain conditions. The extreme nonlinearity of the current-voltage relationship of Josephson junctions makes them ideal for applications in active microwave devices, such as amplifiers, oscillators, and mixers. The distinctive advantages of such superconducting active devices include extremely low noise, very low power consumption (nanowatts), broadband and high frequency operation. The AC Josephson effect established the following voltage-frequency relationship [6]:

$$f = \frac{(2e/h)}{V_0}, \quad 2e/h = 0.4836 \text{ GHz}/\mu\text{V}$$  (1)

where $V_0$ is the DC voltage across the junction when biasing above its critical current $I_0$. Because $2e/h = 0.4836 \text{ GHz}/\mu\text{V}$, for $V_0$ from $\mu\text{V}$ to $m\text{V}$, $f$ falls into the microwave, mm and sub-mm or THz bands. The AC Josephson effect forms the basis for RF signal generation, detection and mixing of the Josephson junction devices. Fig. 2 shows an example of the I-V curves of a junction irradiated with a microwave power[22]. The left I-V curve is without RF radiation and the successive curves to the right are for increasing RF power. Note that the $I_c$ value decreases with increasing RF power and the voltage steps are determined by the $f - V_0$ relationship.

HTS Josephson junctions are made from the HTS thin-film grain boundary formed on bi-crystal, step-edge, biepitaxial or ramp-edge structures because of extremely short superconducting coherence lengths. Due to the nature of grain boundaries, obtaining reproducible HTS Josephson junctions is significantly more difficult than obtaining LTS Josephson junctions with tightly controlled junction parameters. Significant progress has been made over the past three decades on the YBCO thin film quality, junction fabrication techniques and control of the junction parameters, driven primarily by research and development of superconducting quantum interference devices (SQUIDs)[6]. The research group at CSIRO has developed and matured a YBCO/MgO step-edge Josephson junction technology [54] and many novel HTS devices and application systems based on this technology [55], [56]. The advancement of HTS microwave and millimeter wave active devices and circuits based on this YBCO/MgO step-edge junction technology will be presented later sections.

A typical RF receiver front end is configured as shown in Fig. 3, consisting of passive components of filtering networks and active devices for amplifying and frequency down-conversion [57]. The down-converter module, which is marked inside blue box in the figure, is the key circuit part determining the gain and noise performance of the receiver. For a hybrid HTS receiver front-end, the downconverter is built with...
HTS filters and semiconductor amplifiers and mixers and integrated into cryocoolers for operation. Hybrid HTS receivers avoid using HTS Josephson active devices that are difficult to fabricate, thus represent simpler HTS receiver front-ends. However, the interconnections between components, typically thin metal bonding wires, possess inductive and resistive loss characteristics especially when the frequency rises to mm-wave range. The losses introduced by the interconnections of the modules would deteriorate the overall system performance.

Major progress has been made in recent years by the authors group in integrating HTS Josephson active devices into the HTS receiver systems (see Sections IV and V for more details). A schematic of such a HTS receiver front-end based on MMIC Josephson mixer, is shown in Fig. 4 [58]. The HTS MMIC mixer integrates HTS passive components and Josephson junction mixing devices on one single circuit chip, with internal connections using low-loss HTS transmission lines. Therefore, the transmission loss of the HTS MMIC Josephson mixer is reduced, and the HTS receiver incorporating the HTS mixer would feature a better conversion gain and lower noise figure. Additionally, the HTS MMIC Josephson mixer is more compact than the hybrid down-converters, which result in a smaller module size of the front-end. Due to the compact size and the low LO power requirement of the Josephson junction, the HTS front-end module has lower thermal loading and thus requires less cooling power, which is more energy efficient than the hybrid HTS receiver systems.

III. HTS PASSIVE MICROWAVE DEVICES

In the past three decades, various kinds of high-performance HTS filters have been developed and applied in the front-end subsystems in many application fields [59]. Early research was focusing on the low loss and high selectivity of the filter performance, while more advanced filters have been instigated in recent years, typically focusing on the power handling capacity and frequency versatility.

A. LOW-LOSS AND HIGH-Q FILTERS

Typically, a high-performance filter features low insertion loss within the required passband, a high rejection in the stopband, and a sharp skirt slope at the edge of the passband. High stopband rejection and sharp slope can be achieved by increasing the number of the filter’s poles/resonators, but the insertion loss would also increase as the filters based on conventional conductors have relatively high surface resistance. In [60], [61], 5-order filters were reported with insertion loss over 1.1 dB and skirt slop around 30 dB/GHz within the passbands around 8 GHz and 30 GHz respectively. HTS filters, however, features low insertion loss with high-order structures as shown in Fig. 5 [62]. The 12-order filter has an insertion loss of 0.05 dB at 1.3 GHz, and an out-of-band rejection level of 65 dB, which is significantly better than the 5-order filters mentioned above. Such performance can be further improved by introducing transmission zeroes to further increase the skirt slope and stopband rejection, as reported in [14]. The filter demonstrated the highest slope of 300 dB/MHz with 22 poles and 10 zeros, which surpasses the performance of conventional 50-pole Chebyshev filter. HTS filters with superior performance in insertion loss and selectivity at higher
frequency range were also reported in [15], [63], featuring an insertion loss below 0.5 dB and stopband rejection over 50 dB at frequencies up to 24 GHz, which has demonstrated their competence in the application of 5G base station systems. Insertion loss of these filters, although as low as 0.5 dB, was introduced by the material loss of high order resonators, as well as the interconnection loss between HTS circuits and coaxial connectors.

Apart from low loss and high selectivity of filters, modern communication applications also require good consistency of in-band group time delay (GD), while high selectivity typically result in poor in-band GDs. One approach to improve the in-band GD flatness is applying an external group delay equalizer, namely a circulator or a 3 dB directional coupler [64], [65]. The external equalizer usually had opposite GD characteristics to the original filters for equalization, which successfully reduced the in-band GD variation to less than 50 ns without any noticeable degradation of the band-edge steepness of the HTS filter. However, the requirement of external circuit configuration made the overall dimension of the filter bulky.

Another approach to achieve the flat GD characteristics is utilizing the positive cross-coupling between the nonadjacent resonators in the filter synthesis to introduce the transmission zeros at the real axis, which is called the self-equalization method [66]. The positive cross coupling can improve the GD flatness, but the out-band selectivity of the BPF is worsened correspondingly. Therefore, both positive and negative cross-couplings were used in reported designs to improve the GD flatness and the selectivity simultaneously. Typically, [67] reported a 14-pole narrowband HTS filter with a center frequency of 8.625 GHz and a fractional bandwidth of 0.49%. One pair of negative, and two pairs of positive cross-couplings were introduced, resulting in both high band-edge steepness (over 11.7 dB/MHz) and excellent group delay flatness (less than 30 ns over 82% of the passband), as shown in Fig. 6. The self-equalization approach features compact filter size but requires complicated design configuration and accurate control of the cross-coupling.

Compactness is an important design consideration for the passive circuits in HTS MMIC mixers due to limited chip size, and therefore low order filters with cross-coupling configuration is desired for both compactness and selectivity [68], [69]. [69] presented a three-order bandpass filter at 6.5 GHz with a fractional bandwidth of 2%, as shown in Fig. 7. Compared with the five-order hairpin line bandpass filter used in an earlier integrated HTS circuit [70], the three-order filter takes about two thirds the size but produces better selectivity, which makes it suitable for monolithic integration with Josephson junctions.

**B. HIGH POWER HANDLING HTS FILTERS**

On top of the superior performance of low loss and high selectivity, advanced HTS filters have been developed featuring high power handling capacity and reconfigurability, to address the challenge raised by future wireless communication systems. Power handling capacity of an HTS filter is determined by the critical current of the resonators, which is limited by the current concentration at the edge of the microstrip line [71]. Therefore, various designs have been proposed with modified resonator layout to increase the critical current limit,
such as disk resonators [72]–[74] and sliced microstrip lines [17], [75], [76]. Specifically, a 10-pole S-band HTS filter based on special straight-line half-wavelength resonators was reported in [77], showing an out-of-band rejection better than 80 dB and an in-band (2.11–2.19 GHz) power handling capability of 35.8 dBm (3.8W) at 60 K, as shown in Fig. 8, which is a significant improvement compared with previous HTS filters whose typical power handling level was on the order of milliwatts.

C. RECONFIGURABLE HTS FILTERS

The reconfigurability of HTS filters is an emerging research topic to meet the requirements of spectrum agility and versatility in future multi-band, multi-mode wireless systems in radar, satellite and cellular communication applications. Currently, most reconfigurable filters are developed based on ferroelectric, semiconductor devices and radio frequency micro-electro-mechanical system (RF MEMS) technologies [78]. These tunable devices usually possess high resistive loss, which leads to a deterioration in the filters’ performance. Reconfigurable filters at room temperatures typically feature insertion losses up to 5.5 dB [79], [80], which is not acceptable for high-performance wireless systems. The integration of HTS filters with the abovementioned reconfigurable devices would significantly reduce resistive loss, thus the filters insertion loss, and the Q-factor can be improved correspondingly. A 3-pole YBCO/ Ba0.05Sr0.95TiO3 ferroelectric thin film bandpass filter was reported in [81], featuring a tunability of 5.1%, an insertion loss of 2.4–1.4 dB, and a reflection better than 15 dB. A comparison was made by the authors by testing an Ag/Ba0.5Sr0.5TiO3 filter with the same design at room temperature, and an insertion loss of over 10 dB was obtained. Semiconductor varactor-based HTS filters were also investigated [18], [82], [83]. In particular, the 4-pole tunable HTS high-Q bandpass filter reported in [82] showed a center frequency tuning range of 430–720 MHz (50% tuning) with a constant fractional bandwidth of 3%. Fig. 9 shows the filter’s layout and its measurement results. The insertion loss was in the range of 0.8–3.8 dB, and the return loss was better than 10 dB. The superior performance of low insertion loss, ultra-narrow bandwidth and wide tuning range were achieved simultaneously due to low loss of YBCO film and the high Q-factor of the varactor.

RF MEMS technology, including MEMS switches and varactors, features compact size, very low loss, high linearity, and high power-handling capacity at microwave frequencies [84]. LTS niobium-based superconducting micro-fabrication process was well developed which enabled the monolithic integration of gold-based RF MEMS devices with niobium superconducting RF circuits [85], and reconfigurable MMIC LTS resonator and filter have been developed [86]. The reported Nb reconfigurable bandstop filter demonstrated a sweep of frequency from 2.62 to 2.54 GHz and a discrete shift from 2.54 to 1.95 GHz. Compatibility of MEMS fabrication process has also been explored for HTS filters, as reported in [87]. A 2-pole HTS/MEMS tunable bandpass filter was developed with a tandem 9-bit MEMS capacitor array. The HTS/MEMS hybrid filter demonstrated a high performance, specifically an ultra-narrow band width of 1 MHz, a center-frequency tuning range from 755–580 MHz and an insertion loss of 0.7–4 dB,
as shown in Fig. 10. The filter shows a promising prospect of the HTS/MEMS filter in future wireless system applications.

However, MEMS devices may function abnormally at cryogenic temperatures, which has been reported in [88]. 28 MEMS switches were tested at cryogenic temperature, and only 13 of them still performed properly. Therefore, there is a potential risk of large-scale application of MEMS device on HTS filters.

Conclusively, HTS passive circuits feature superior performance compared with their room-temperature counterparts at microwave/mm-wave frequencies, and their integration with semiconductor tunable devices enables low loss, high Q-factor and wide tuning range, which are highly desired features for future wireless communication and detection systems.

IV. HTS ACTIVE MICROWAVE DEVICES
A. JOSEPHSON OSCILLATORS AND MIXERS

HTS oscillators and mixers have been developed utilizing the nonlinearity of the current–voltage (I–V) relationship of Josephson junctions. Relatively simple HTS MMIC circuits were developed in 1990s by Suzuki et al. [58], [46], [47] who integrated Josephson junctions with HTS filters and antennas. A generation of sub-mm wavelength radiation has been demonstrated in oscillators based on discrete Josephson junction arrays in [7]. High-frequency signal was generated at above 100 GHz, although the power was as low as -54 dBm. In 1992, intrinsic Josephson effects behavior in HTS Bi$_2$Sr$_2$CaCu$_2$O$_8$ single crystal was observed [7], where the series arrays of Josephson junctions were formed from the naturally grown crystal lattices. HTS signal emitters have been developed based on these intrinsic BSCCO junction arrays, ranging from 0.5 to 1.5 THz, and the best devices presently reached an output power around 100 μW [8]. Likewise, various HTS junction-based mixers ranging from microwave to THz frequencies have also been reported [9]–[11], [19]–[22].

A novel frequency-tunable HTS oscillator was reported in 2008 [24], based on a resistive-shunted SQUID (R-SQUID) configuration [23]. As shown in Fig. 11, a resistor made of a gold thin film interrupting a superconducting loop connecting two junctions (i.e., a typical DC SQUID configuration), resulted in a differential voltage across the resistor when applying a DC current $I_R$. This voltage gives rise to a

FIGURE 10. (a) AutoCAD drawing of the HTS 2-pole constant bandwidth filter with tandem 9-bit MEMS capacitor arrays, with DC bias connections shown at the top, and filter circuit at the bottom; (b) different transmission response (S21) under various bias conditions [87].

FIGURE 11. (a) Schematic circuit diagram and (b) photo of the resistive RSQUID oscillator/mixer device showing a 2-junction shunted by Au thin-film resistor (the junction width and length are 2 μm and 10 μm respectively, and (c) a self-pumped frequency mixing spectrum [24].
heterodyne oscillation frequency according to the Josephson AC effect (equation 1). The heterodyne voltage and thus the oscillation frequency can be easily tuned by adjusting the $I_R$ value. A wide frequency tuning ranges from 0.1 to 2 GHz was demonstrated. Subsequently, a combined HTS local oscillator and mixer device with tunable frequency was demonstrated [24], [89]. Mixing of microwave frequencies between 1 and 5 GHz and IF frequencies between 200 MHz and 4 GHz were achieved. The novel oscillator/mixer device features low power consumption and high frequency agility, and both are critical characters for future reconfigurable wireless receiver systems. Phase noise of the generated signal can be reduced by the application of phase lock loop (PLL), or a high-Q resonator, but the tuning range would be reduced consequently.

**B. HTS MMIC MICROWAVE MIXERS/RECEIVERS**

Integration of the HTS passive and active components onto a single chip to form a functional HTS microwave circuit is highly desirable but has always been extremely challenging. Early attempts of integrating HTS components on-chip were trialed [46], [90], and a conversion gain around -15 dB at 15 K was reported in [58]. Major progress has been made in recent years by the authors group in developing the HTS monolithic microwave integrated circuit (MMIC) combining HTS passive and active devices to achieve both low loss and high compactness. A few state-of-art developments are presented below.

Based on the novel R-SQUID oscillator/mixer configuration described in [24], [89], an HTS MMIC R-SQUID downconverter circuit was developed [70], [91]. Fig. 12(a) shows the photo of a HTS MMIC downconverter circuit module, which incorporated a R-SQUID oscillator/mixer device with HTS bandpass and lowpass filters on a single 20 × 10 mm MgO substrate. LO signal was generated internally from the R-SQUID loop with a wide tuning range from 2 to 7 GHz. The interconnection between the passive circuits and the Josephson junction are the HTS transmission lines instead of metal bonding wires, thus significantly reduced the connection loss. The overall conversion gain of the module was measured to be -15 dB at 30 K and -10 dB at 15 K as shown in Fig. 12(b), which is a promising result without an external LO input. Despite a relatively high phase noise due to lack of phase-lock loop devices, the downconverter featured compactness, low power consumption, and a wide LO tuning range.

Fig. 13 shows a 10–12 GHz HTS MMIC mixer/ downconverter that consists of a Josephson junction and passive circuits on a single chip [48]. In this design, an eight-pole filter was applied on stepped-impedance hairpin resonators for a compact size and high selectivity. A low-pass filter (LPF) and a LO resonator were designed for port isolation and better coupling efficiency. The mixer’s demonstrated an average conversion gain of -5 dB at 40 K and -3 dB at 20 K with a maximum value of -1 dB, which is the best performance reported in literatures at this frequency band. It was a significant improvement compared with the mixer from the earlier work by [58] with only half of the chip size used. The increase in conversion gain was mainly due to the difference in
the optimized junction characteristics and efficient integration of the active and passive HTS circuits, an approximate 7 dB gain compared to a similar step-edge junction mixer without on-chip HTS filters [92], while the compactness of the mixer circuit was improved by the designs of filters.

More HTS MMIC mixers were further developed following the design principle at various frequencies up to Ka-band [49], [58], [93], with the pursuit of low loss and compact size. In particular, a 36 GHz HTS MMIC mixer in [49] was developed on a 4.5 \times 4 \times 0.3 \text{mm}^3 \text{MgO} substrate as shown in Fig. 14(a). The circuit between the Josephson junction and the RF input port functioned as RF filter, DC biasing, and impedance matching. The IF link also served multiple purposes, as a low pass filter and a virtual grounding for RF signals. The compactness of the circuit was consequently increased significantly. Measured frequency response of the mixer’s conversion gain is shown in Fig. 14(b). Maximum conversion gain of $-7$ dB at 37 GHz was obtained at 40 K and was as high as $-1.5$ dB at 20 K, which is amongst the best HTS mixer performances reported at similar frequencies.

**C. OPTIMIZATION BY IMPEDANCE MATCHING AND JUNCTION ARRAY**

Apart from the optimization of the passive circuit for low loss, the performance of an HTS Josephson mixer can be improved by optimizing the impedance matching of the Josephson junctions with the circuit ports. Typically, the intrinsic resistance of a step-edge Josephson junction is between 2 and 8 $\Omega$, and it is supposed to be matched to the 50 $\Omega$ circuit ports. With limited space on the circuit chip, the matching to 50-$\Omega$ RF port can only be achieved within a narrow bandwidth, typically below 10% of the center frequency. Therefore, an increase of the Josephson junction resistance or impedance is essential for better mixer performance, but a high junction resistance is very difficult to obtain due to the intrinsic resistively-shunt nature of HTS Josephson junctions. An alternative approach was adopted in [50] with the application of a cascaded Josephson junction configuration as shown in Fig. 15. A cascaded array of three junctions is designed, which leads to a significant improvement of impedance matching between the RF port and the junctions, and thus a 4 dB improvement in conversion loss. The average conversion loss within the RF frequency range is 5 dB with a variation of 1 dB, operating at 40K, which is among the best performance of HTS Josephson mixers at comparable frequencies and operating temperatures.
The performance of the HTS mixer was also compared with other non-superconducting mixers at similar frequency range and the presented one demonstrated better performance in conversion and image-reject ratio. The junction array mixing configuration provides a novel approach of improving impedance matching, which enables high-performance circuit designs with a broader bandwidth.

V. HTS CIRCUIT MODELLING METHODS

Modelling is critical in circuit designs because it provides theoretical guidance for circuit designs and optimizations. Theoretical investigations have been reported on the modelling of Josephson junctions’ mixing effects [94], [95], which were based on more ideal low-temperature superconducting junctions and for single junction mixer element alone. A modelling approach for HTS Josephson mixer was developed by Pegrum et al. [51] who used the well-tried and freely available Josephson simulator JSIM [96]. The mixing circuit model was simplified by using ideal AC current sources for the RF and LO inputs as shown in Fig. 16. The modelling approach successfully simulated the mixing behavior of the Josephson junction, exhibiting the IF spectrum and extra harmonics. Simulation results were compared with experiments, and qualitative agreement was reached in the results of biasing conditions and linearity. The modelling method using JSIM provided an effective, economical, and fast approach to investigate the junction’s optimal operation condition.

However, the performance of the MMIC Josephson mixer is determined by not only the Josephson junction characteristics, but also by the transmission responses of the passive filter circuits as well as the coupling efficiency of these filters to the input and output of the Josephson junction. Therefore, modeling and simulation of HTS MMIC Josephson mixers containing HTS passive and active devices will provide a better theoretical guidance for the circuit design and optimization. A new modelling method was consequently developed by Zhang et al [52], based on Keysight’s Advanced Design System (ADS), a high-performance microwave design and simulation package, combined with Josephson model. The Josephson junction was modelled in Verilog-A, and imported to ADS for transient simulations. Thermal noise of the junction’s intrinsic resistor, a critical factor to its characteristics, was added to the model as an external shunted resistor. Fig. 17 shows the schematic block diagram of our HTS MMIC simulation model. RF, LO and IF ports are set to be loaded with 50 Ω terminals. This modelling approach enabled independent investigation of impedance at different ports. Optimal impedance matching was able to be investigated by sweeping the filters’ port impedance values, which provides important goals for the passive circuit designs.

The modelling method was testified for its validity by comparing the simulation results, as shown in Fig. 18(a) and (b), with the measurement results of developed sample shown in Fig. 18(c) [58]. The simulation results agreed with measurements well in the suppression behaviors of I-V curves by application of LO power. The simulation result of IF power versus the DC bias current was also consistent with measurement, with the double-peak behavior and the operation range difference observed. The model successfully demonstrated the
function of the Josephson junction and HTS filters, and ascertain that the mixing performance optimization can be achieved with properly matched filtering networks.

VI. MODULE DESIGN AND SYSTEM INTEGRATION WITH LNA AND CRYOCOOLER

A. MODULE INTEGRATION WITH SEMICONDUCTOR DEVICES

Various efforts have been made towards the system integration of HTS Josephson mixers for their potential application in wireless communication systems. One important work was the module integration of HTS Josephson mixers with cryogenic low-noise amplifiers (LNA). Several frequency down-conversion modules have been developed around Ka-band for low noise and high gain [58], [93]. In [58], a compact, high-gain and low-noise Ka band HTS receiver front-end module was reported. A semiconductor low noise amplifier and HTS monolithic Josephson mixer are packaged together into a compact front-end module as shown in Fig. 19(a). HTS passive and active devices are integrated monolithically on a single MgO substrate to reduce the transmission loss and achieve higher conversion efficiency. The total size of the packaged module including the biasing circuits and housing is below 25 mm × 20 mm × 15 mm, which is very compact. Measurement results in Fig. 19(b) and (c) show a conversion gain of 40 dB and noise figure around 0.5 dB for the presented new receiver front-end at 40 K. Such performance and compactness feature demonstrated the potential of the HTS front-end receiver technology for Ka band high-speed, long-range communications.

For the Ka receiver front-end, other issues were observed that impacted the performance of the module. The first problem is the interference introduced by cavity resonance. For module designs at the frequency over 30 GHz, cavity resonance can affect the performance of the whole module and can no longer be neglected. Cavity resonance was discovered in the passband of the front-end mentioned above, and a piece of electromagnetic absorber film was applied to the top of the
mixer area to eliminate a cavity resonance. The absorber was found to have introduced extra loss to the filter and resonator during the measurement. The cavity resonance interference could be avoided by optimizing the module design as reported in [49]. By optimizing the module design shown in Fig. 20(a), the interference introduced by the cavity resonance could be suppressed in the circuit area, as shown in Fig. 20(b). Another issue observed was the potential malfunction of LNA circuits. While cryogenic LNA chip dies are hard to acquire due to limited supplies, room-temperature LNA MMIC chips are an alternative solution in many applications. However, the biasing condition of the LNA might change dramatically when working at cryogenic temperatures, resulting in the drop of gain or even self-oscillation [93]. Characterization of the LNA chips alone at cryogenic temperatures is necessary before the system integration.

B. INTEGRATION OF HTS CIRCUIT WITH CRYOCOOLER

The main challenges of the cryogenic integration of the system include minimizing both the heat load and the electrical losses, and the cryocooler-associated electromagnetic noises. The electrical loss depends on the electrical conductivity of the cables and wires feedthrough the cryocooler, of which the electrical and thermal conductivity are typically proportionally related. Various considerations and compromises must be made. The overall heat loading of the HTS modules needs to be minimized due to limited cooling power provided by the cryocoolers. Fig. 21 shows the schematic diagram of a 20 GHz cryogenic LNA module operating at 80 K [97]. A commercial waveguide feedthrough was applied at the input of the module to provide low electrical loss and good thermal insulation. The total insertion loss of the input link before the LNA stage was 0.25 dB, while the measured gain of the module is 4 dB higher than room-temperature LNA modules. Additionally, the noise temperature decreases from above 120 K at room temperature to lower than 40 K at operating temperature of 80 K. The compact size of the overall system allows integration on moving platforms, which enables the application of high-performance aerospace/satellite communications.
The integration of Josephson devices with miniaturized cryocoolers has been another significant progress made for practical applications. Josephson junctions are very sensitive to magnetic fields, which raised extra challenges to the integration of HTS circuits with portable miniaturized cryocoolers. A successful demonstration of the integration of an HTS MMIC receiver system with a commercial single-stage mini cryocooler was reported by the authors group [27], which is shown in Fig. 22. The orientation of the split compressor and the cold finger were designed and implemented in such a way that the HTS step-edge junction would see minimum vertical magnetic flux generated by the compressor. This portable HTS Josephson microwave receiver circuit was operated successfully in the mini cryocooler unshielded, demonstrating great potential for applications in wireless communications systems.

VII. CONCLUSION
In the past 20 years, great efforts have been made to the research and development of HTS devices, circuits, modules and system integrations for microwave/mm-wave receivers. HTS filters have demonstrated excellent performance with low insertion loss, high selectivity, flat in-band group delay, as well as high power capacity and frequency tuneability. Major progress has been made in developing HTS Josephson oscillators/mixers and their MMIC circuits combining HTS passive circuit and active Josephson devices. Significant performance improvement in conversion gain and noise figure has been achieved in these state-of-art HTS MMIC mixers/receivers credited to the design optimization by novel theoretical modelling methods and continuous improvement of the YBCO/MgO step-edge Josephson junction characteristics. The successful demonstration of system integration of HTS circuits with commercial mini-cryocoolers made a further step closer to practical applications and industry adoption of the HTS receiver systems for future high-performance microwave/mm-wave wireless communication systems. It is expected that we will see growing applications of HTS technologies in wireless and satellite communications and sensing systems in not long-distance future.

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