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高温超导滤波器及其应用研究进展

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摘要 高温超导材料的微波表面电阻比铜等金属小将近3个数量级，所以自从高温超导材料发现以来，人们就开始了高温超导微波滤波器的研究，并研制出了各种各样具有低损耗、高选择性、优异的带内群时延特性等性能优异的高温超导滤波器. 与此同时，高温超导滤波器的应用研究也取得长足进步. 目前，由高温超导滤波器、微型斯特林制冷机及半导体低噪声放大器等组成的高温超导微波前端子系统已经在移动通信、雷达、深空探测和卫星通信等多个领域获得应用并取得了显著的经济和社会效益. 近年来，高温超导滤波器的研究也在不断地向新的方向拓展，在大功率承载能力、多通道器件、可调频率滤波器以及全超导接收机等领域取得显著进展. 本文对高温超导滤波器的研究现状和应用进展进行总结，并对高温超导滤波器及微波应用的研究发展趋势进行展望.

关键词 高温超导，滤波器，移动通信，空间应用，雷达，射电天文

随着现代工业化的发展，微波频谱变得越来越拥挤，微波频率资源也越来越珍贵，这对微波滤波器提出了越来越高的要求：微波滤波器不仅要具有很高的带外抑制和陡度来抑制各种各样的干扰，而且要具有很小的插入损耗以降低整个接收系统的噪声水平，甚至有些微波系统还要求滤波器具有特定的带内平坦度以降低信号失真. 由于材料本身微波损耗的限制，传统金属材料和元件制作的滤波器往往难以满足上述要求. 在微波频段，高温超导材料的微波表面电阻比铜等金属小将近3个数量级，所以利用高温超导材料可以研制出满足现代微波通信需求的高性能微波滤波器. 在过去的30年中，高温超导滤波器的研究取得了长足进展和丰硕成果，人们研制出了各种各样具有低损耗、高选择性等优异性能的高温超导滤波器. 目前，高温超导滤波器及其前端子系统已经在移动通信、雷达、深空探测和卫星通信等多个领域获得应用. 同时，高温超导滤波器的研究也在不断地向大功率、多工器及可调频率等新的方向拓展. 在本文中，我们对高温超导滤波器的研究情况进行总结，并着重介绍最近5~10年内的研究趋势和应用进展.

1 高性能高温超导滤波器的研究情况

同传统微波滤波器相比，高温超导滤波器可以单独或同时具有极低插入损耗、极窄带、极高频率选择性和带内群时延平坦度等优异性能.

1.1 插入损耗

对于微波接收系统来说，前置滤波器的插入损耗越小越好. 滤波器的插入损耗与其相对带宽、中心频率和滤波器阶数成反比关系. 得益于超导材料的极小的微波表面电阻，高温超导滤波器往往在较小相对带宽和较高阶数的情况下还能保持相对较小的插入损耗. 纵观过去20年文献中出现的超导滤波器，

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Li C G, Wang X, Wang J, et al. The high temperature superconducting filters and its application progress (in Chinese). Chin Sci Bull, 2017, 62: 4010–4024, doi: 10.1360/N972017-00837

绝大多数插入损耗都小于1 dB. 对于相对带宽较宽的高温超导滤波器, 比如文献[1~3]中相对带宽大于20%的高温超导滤波器, 插入损耗都小于0.05 dB. 这样水平的插入损耗即使是对于像深空探测这样对损耗敏感的微波接收系统来说都是可以忽略的. 对于相对带宽极窄的超导滤波器, 插入损耗也能保持在很小的水平. 2005年英国的Hong等人[4]曾经研制了一款用于移动通信的10阶准椭圆函数高温超导滤波器. 该滤波器中心频率位于2 GHz, 相对带宽为0.5%, 而最终测得的插损只有0.2 dB. 在2010年, 中国科学院物理研究所(以下简称中科院物理所)Cui等人[5]研发的一款10阶相对带宽0.45%中心频率2.185 GHz的高温超导滤波器插入损耗低至0.15 dB.

1.2 相对带宽

由于材料本身损耗的限制, 传统滤波器往往做不到小的相对带宽. 因为随着相对带宽的降低, 滤波器插入损耗急剧增大甚至难以成带. 而得益于超导材料的极低微波损耗, 高温超导滤波器可以实现非常小的相对带宽. 大部分超导滤波器可以很容易地实现1%左右的相对带宽, 而通过选择合适的谐振器和耦合结构, 有的超导滤波器甚至能实现小于千分之一的相对带宽. 美国Conductus公司的Dustakar和Berkowitz[6]曾经研制了一款中心频率位于700 MHz而相对带宽只有0.014%的高温超导滤波器. 值得指出的是, 该滤波器插入损耗只有1.37 dB, 对应的谐振器Q值高达135000. 2009年, Kawaguchi等人[7]又报道了一款中心频率为5.370 GHz、相对带宽为0.056%的高温超导滤波器, 其插入损耗也仅为2.04 dB. 中科院物理所Li等人[8]去年报道了一款C频段相对带宽0.02%的高选择性滤波器, 在这么高的频段其插入损耗大约为3.8 dB.

1.3 带外抑制和带边陡度

高温超导滤波器的高带外抑制和带边陡度来自于两个方面. 一方面得益于超导材料的低损耗, 高温超导滤波器可以具有很高的阶数. Hattori等人[9]和Liu等人[10]都曾经研制过达到20阶的超导滤波器. Zhang等人[11]曾经报道过一款24阶的超导滤波器, 其带边陡度为17 dB/MHz, 60 dB/3 dB矩形系数达到了1.08, 带外抑制超过90 dB. 另一方面近20年来滤波器的设计理论取得了长足进步, 基于谐振器耦合理论的泛车比雪夫(准椭圆函数)滤波器的设计技术日趋成熟[12], 可以通过引入谐振器间的交叉耦合实现滤波器传输零点来提高带外抑制或带内群时延平坦度. 超导滤波器的二维平面结构比较适宜于引入或实现各种各样的交叉耦合. Li等人[13]曾设计过用于气象雷达的10阶泛车比雪夫超导滤波器, 通过引入一对交叉耦合, 其带边陡度达到120 dB/MHz. Li等人[14]为第三代移动通信设计的12阶超导滤波器引入了3对交叉耦合零点, 使滤波器的带边陡度达到了140~220 dB/MHz, 远带抑制超过100 dB. 带边陡度最高的超导滤波器是日本的Tsuzuki等人[15]研发的一款22阶5对传输零点的滤波器(如图1所示), 其带边陡度达到300 dB/MHz, 偏离带边350 kHz处的抑制就达到了90 dB. 该滤波器的陡度已经可以媲美于50阶的车比雪夫滤波器.

1.4 带内群时延

在一些数字通信中, 不但对滤波器的选择性有

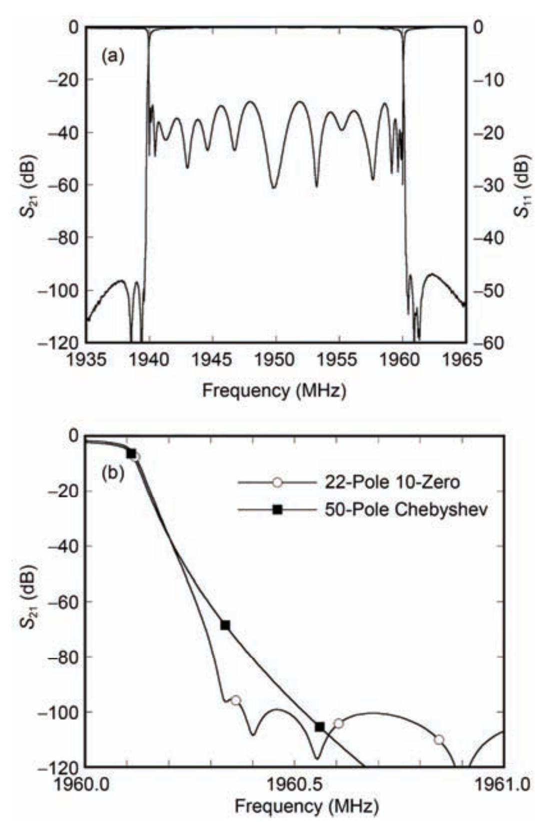

图1 日本的Tsuzuki等人[15]研发的一款22阶5对传输零点的滤波器. (a) 该滤波器的传输特性曲线; (b) 该滤波器与50阶车比雪夫滤波器的带边陡度对比

Figure 1 The 22-pole HTS filter with 5 pairs transmission zeros developed by Tsuzuki et al[15]. (a) S_{11} and S_{22}; (b) comparison of band edge steepness with 50-pole Chebyshev filter

高要求，而且还会对带内群时延特性提出较高要求．而对滤波器来说带内群时延和带外抑制(特别是带边陡度)是一对矛盾的指标，高带边陡度会带来带内群时延的恶化．一般来说，有两种办法可以改善滤波器的群时延特性．一是在滤波器后面级联一单独的群时延均衡器[16,17]；二是在滤波器设计时就引入带内虚传输零点来改善群时延特性[18~20]．前者代表性工作可见Sun等人[16]设计的一款用4阶群时延均衡器级联的10阶泛车比雪夫滤波器[17]，通过外部群时延均衡器的引入可以使滤波器有效带宽从50%增加到70%．而后者如Gao等人[20]设计的14阶自均衡滤波器(如图2所示)，通过引入一对实传输零点和两对虚传输零点，既得到了较高的带边陡度又得到了较好的带内群时延特性，滤波器60 dB/3 dB矩形系数好于1.25，而在82%的通带带宽内群时延波动小于30 ns.

2 超导滤波器发展的新趋势

2.1 大功率超导滤波器

前面讲述的各种高性能的超导滤波器能承受的

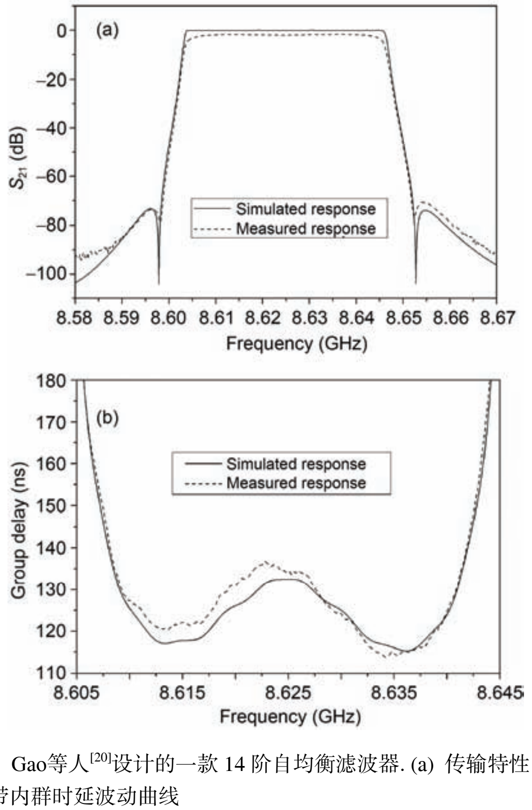

图 2 Gao等人[20]设计的一款 14 阶自均衡滤波器. (a) 传输特性曲线; (b) 带内群时延波动曲线

Figure 2 The 14-pole self-equalized HTS filter developed by Gao et al[20]. (a) S_{21}; (b) group delay

微波功率有限，一般在几十毫瓦量级，所以目前超导滤波器主要应用于微波系统的接收端而非发射端．应用于发射端的滤波器需要能承受较大的微波功率，一般从几瓦到上千瓦．研制能承受大功率的滤波器一直是超导滤波器研究的一个难点和努力方向．限制超导滤波器功率承受能力的根本因素在于超导薄膜本身临界电流的限制．由于高温超导滤波器通常采用微带结构，随着微波功率的增强，微带线内电流密度增大，当电流密度接近超导材料临界电流密度时，微带线损耗会明显增大．而增大的微波损耗会使微带线局部发热，局部发热又进一步降低临界电流密度，从而使得整个超导滤波器失超．所以，在现有超导材料下提高超导滤波器的功率承受能力主要手段是改善谐振器结构，降低在特定功率下超导材料内的电流密度.

在早期，人们主要采用片状谐振器来提高滤波器的功率承受能力[21~23]．不同于微带谐振器，这些片状谐振器通常工作于TM_{01}或TM_{11}模式，在谐振状态下其电磁场局限于片状超导膜和地之间，从而使谐振器边缘的电流密度很小．采用这种结构的超导滤波器功率承受能力可以达到100 W[21,23]．但是这种滤波器的缺点也是很明显：一是其尺寸非常大，以中心频率2 GHz为例，单个谐振器的直径就将近2 cm，制作一个3阶的滤波器需要的超导基片直径就得超过3 in (1 in=2.54 cm)；二是由于TM模式的谐振模式非常密集，其高次谐振峰与工作频段非常接近，从而使滤波器高端抑制非常差.

近年来仍然有大量的工作致力于提高超导滤波器的功率承载能力，其中不仅包括块状谐振器[24~26]、带状线谐振器[27~32]等非微带线类谐振器，也包括新型结构的微带线谐振器[33~42]．日本一个研究组近几年在$DyBa_2Cu_3O_y$块状谐振器和带状线谐振器上做了大量工作，目前其在块状谐振器结构的滤波器上得到的最大功率承载能力为20 K下114 W(70 K下33.8 W)[26]，如图3所示．而基于双模带状线结构谐振器的滤波器其最大功率承载能力为60 K下31 W(44.9 dBm)[32]．对于微带线结构谐振器，增大功率承受能力主要是通过开槽和增加线宽等手段增大谐振器内电流分布区域从而降低电流密度峰值．虽然相对于块状和带状线谐振器来说微带线结构滤波器功率承载能力仍然偏小，但由于微带线结构谐振器尺寸小、制作简单、易实现交叉耦合等优点，还是吸引了研究人员的

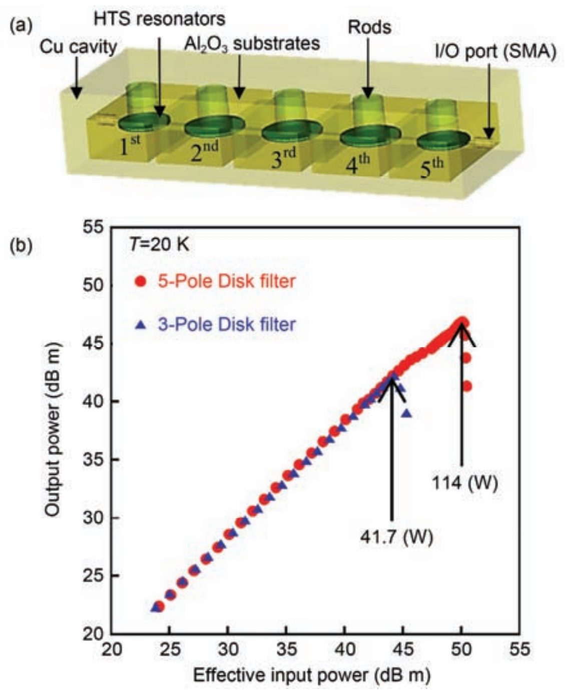

图3 (网络版彩色) Tsurui等人[26]研制的$DyBa_2Cu_3O_y$块状谐振器大功率滤波器. (a) 结构示意图; (b) 功率测试曲线

Figure 3 (Color online) The high power handling $DyBa_2Cu_3O_y$ bulk resonator filter reported by Tsurui et al[26]. (a) The schematic of the filter structure; (b) the measured power handling capability

注意. 例如Bai等人[40]就用微带线结构谐振器研发了一款既具有较高带外抑制又具有较大功率承载能力的超导滤波器. 这款中心频率2.15 GHz、相对带宽4.8%的超导滤波器带外抑制超过80 dB, 而60 K下功率承载能力达到35.8 dBm(3.8 W).

2.2 多通带超导滤波器

随着微波频谱变得越来越拥挤, 微波频率资源也越来越珍贵, 微波通信系统中多频道接收/发射机越来越普遍, 其对多通带微波滤波器的需求也越来越多, 这促使了近年来对多通带超导滤波器的研究发展. 多通带超导滤波器通常有下列4种实现方法.

第一种方法是针对每个通带设计单独滤波器, 然后将各滤波器用微带分支线连接起来. 文献[43]中就用T形分支线连接了两个8阶的带通滤波器, 得到了一个结构紧凑、性能优异的超导双工器. 整个双工器尺寸仅有42 mm×26 mm, 插入损耗仅为0.2 dB, 且通道隔离度达到80 dB. 加拿大的Mansour和Laforge[44]用这种办法研制了三通带的超导滤波器.

第二种方法是用一个带通滤波器级联一个或多个带阻滤波器, 用带阻将带通的单个通带分割成多个通带[45,46]. 例如文献[46]中就是将一个$\lambda/2$单螺旋结构的微带线带通滤波器和一个$\lambda/4$微带线带阻滤波器设计在一起形成一个两通带的带通滤波器.

第三种方法是利用频率变换[47]或耦合矩阵优化[48]来直接设计多通带滤波器. 天津海泰公司曾经设计过一款14阶的双通带超导滤波器(如图4所示)[48]. 他们在滤波器参数综合时引入3对实频率零点, 其中两对位于通带外用于改善带边陡度, 而第3对零点则位于通带内部从而将原通带分割成两个通带.

第四种方法是利用双模或多模谐振器来设计多通带滤波器. 近几年日本的Sekiya研究组[49,50], 中国清华大学曹必松研究组[51~54]和华东交通大学刘海文研究组[55~59]在这方面做了大量工作. Sekiya等人[49,50]用双模谐振器设计了一个8阶双通带带通滤波器, 并与另一个单通带滤波器一起组成了一个三通道超导滤波器[50]. Song等人[51]和Liu等人[55,58]分别用三模微带线谐振器直接设计出了三通道超导滤波器, 如图5所示.

2.3 可调频率高温超导滤波器

现代通信、雷达, 尤其是电子对抗对于频率可变的微波接收设备的需求越来越迫切. 可调频率滤波器是其中的关键部件. 同其他调谐机制相比, 电调谐的可调频率滤波器具有可调范围大、调谐速度快以及尺寸小等优点[59], 已经在各种微波接收设备中得到了广泛应用. 采用超导技术可以大大降低可调频率滤波器的微波损耗, 因此近几年可调频率超导滤波

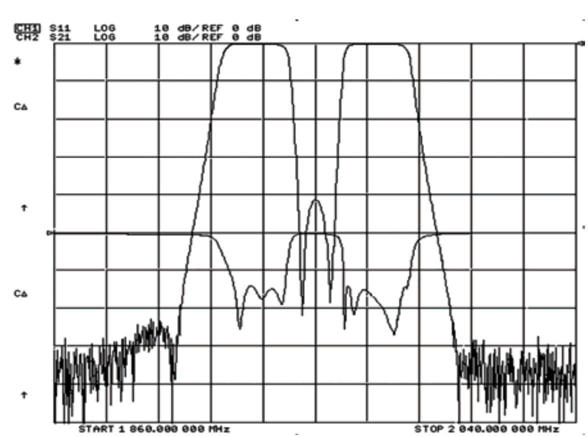

图4 Ji[48]研制的双通带超导滤波器测试曲线

Figure 4 The measured response of a dual band HTS bandpass filter developed by Ji[48]

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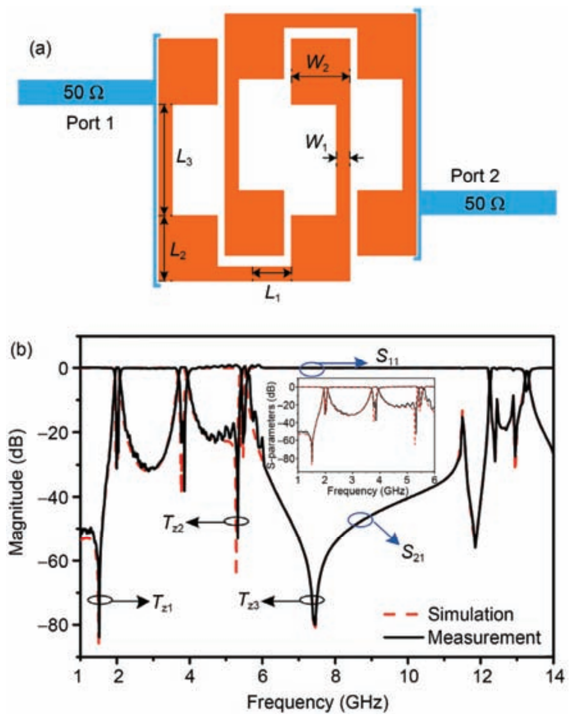

图 5 (网络版彩色)Liu等人[55]用多模阶跃阻抗开口环谐振器设计的三通道超导滤波器. (a) 滤波器版图; (b) 测试曲线

Figure 5 (Color online) A triple-band HTS filter based on a multimode stepped-impedance split-ring resonator reported by Liu et al.[55]. (a) The layout of the filter; (b) the measured responses

器成了一个热点研究方向. 目前可调频率超导滤波器有3种调谐机制: 一是铁电材料调谐; 二是半导体变容二极管调谐; 三是射频微机电系统(radio frequency micro-electro-mechanical system, RF MEMS)调谐.

采用铁电材料调谐具有可调率高、速度快和功耗小的优点. 常用的铁电材料$Ba_xSr_{1-x}TiO_3$(BST)和Strontium Titanate(STO)居里温度在35~400 K之间[60]. 用于微波调频时希望材料的居里温度稍低于工作温度以避免滞回效应并获得较小的损耗[61], 因而可调频率超导滤波器中通常采用x值小于0.1的BST或者是STO薄膜. Tan等人[62]曾经报道过一款采用$Ba_{0.1}Sr_{0.9}TiO_3$薄膜的3阶可调频率超导滤波器. 该滤波器采用超导开口环状谐振器, 而$Ba_{0.1}Sr_{0.9}TiO_3$薄膜位于开口环的开口处, 形成可变电容. 在77 K并最高加以200 V电压时, 该滤波器中心频率可以从11.74 GHz调谐到11.93 GHz(可调率1.6%), 插入损耗在1.6~0.35 dB之间. Su等人[63]对其研制的YBCO/$Ba_{0.05}Sr_{0.95}TiO_3$三阶带通滤波器的每一个谐振器都单独调谐, 从而获得良好的反射损耗. 该滤波器可调率为5.1%, 插入损耗在2.4~1.4 dB之间. 作为比较, 他们同时制作了同样结构的Ag/$Ba_{0.5}Sr_{0.5}TiO_3$滤波器, 其插入损耗高达28~10 dB. 俄罗斯的Vendik等人[64]用STO制成了独立的电容元件, 并用STO电容设计了2阶的超导滤波器, 其插入损耗为3.5~2 dB. 同样如果将超导材料换成铜的话插入损耗升高到6~5 dB.

半导体(主要是砷化镓)变容二极管, 具有可靠性高、调谐速度较快(~GHz/μs)以及尺寸小等优点. 目前传统的可调频率滤波器主要就是采用砷化镓变容二极管调谐的. 最近几年有多个工作采用砷化镓变容二极管研制出了颇具实用性的超导滤波器[65~67]. 2014年Li等人[65]研制了一款相对带宽3%的4阶可调频率超导滤波器(图6). 该滤波器采用Macom公司的砷化镓变容二极管作为调谐元件, 而且对每个谐振器进行了精心设计, 使得4个谐振器可以用同一电压同时调谐, 大大减小了调谐的复杂性. 在2.4~20 V的调谐电压变化下, 可调频率范围为430~720 MHz (可调率50%), 如图7所示. 而整个可调范围内插入损耗在0.8~3.8 dB之间.

Wang等人[66]用砷化镓变容二极管研制了相对带宽2.5%的可调带阻滤波器, 其可调频率范围为286~485 MHz(可调率52%), 带内抑制26~70 dB, 而阻带外损耗小于0.2 dB.

用于可调频率滤波器的MEMS器件包括MEMS开关和MEMS电容两种, MEMS器件一般通过静电吸

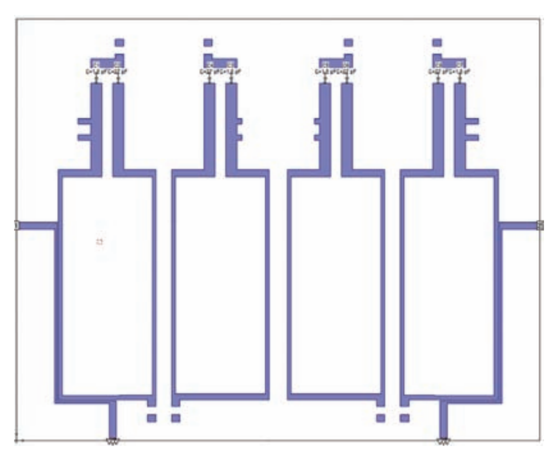

图 6 (网络版彩色)Li等人[65]研制的相对带宽 3%的 4 阶可调频率超导滤波器. 图中每个谐振器上部串联一个标称值 1.5 pF的可调变容二极管和一个 27 pF的隔直电容

Figure 6 (Color online) A four pole tunable bandpass HTS filter with a fractional bandwidth of 3% developed by Li et al[65]. In this filter, each microstrip line resonator was in series with a 1.5 pF varactor diode and a 27 pF capacitor

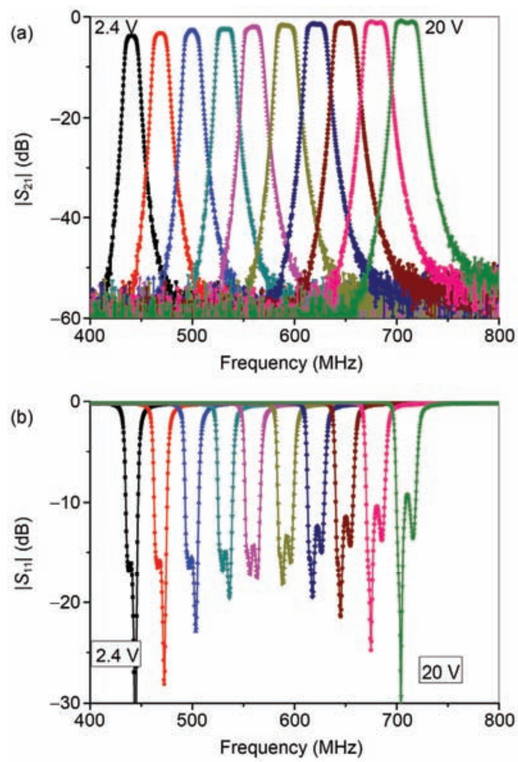

图 7 (网络版彩色)在 2.4~20 V的调谐电压变化下, 可调频率范围为 430~720 MHz(对应可调率为 50%)[65]

Figure 7 (Color online) The filter shows a tuning range of 430–720 MHz with a bias voltage of 2.4–20 V(50% tunability)[65]

力和斥力动作[68,69], 具有尺寸小、损耗小和功率承受能力高的优点[70,71], 所以超导和MEMS器件的组合有望产生最具潜力的低损耗可调频率滤波器. Prophet等人[72]曾经报道了一款2阶的HTS/MEMS可调频率滤波器. 该滤波器采用了9个MEMS开关的阵列来控制9个不同电容的取舍, 可以实现0.2~2 pF之间一共512个不同的电容取值. 该滤波器可调频率范围为755~580 MHz, 插入损耗0.7~4 dB. 考虑到该滤波器带宽只有1 MHz, 上述插损对应到谐振器Q值可以高达7000. 但目前MEMS器件的可靠性还有待提高, 大大限制了其应用. Su等人[73]曾经在低温下测试了28个MEMS开关, 结果这28个在室温下工作良好的MEMS开关只有不到一半能在80 K下工作.

2.4 全超导接收前端

通常微波接收机都是下变频式的, 其主要组成部件除了前置滤波器外, 还有天线、低噪放、本振和混频器等. 目前采用超导技术的微波接收机大多仅仅是在天线下、中频前使用超导滤波器+置于低温环境的半导体低噪放的所谓超导微波前端, 而天线、本振和混频器还都是传统的金属和半导体器件. 可以想象, 如果能将这些半导体器件全部替换成超导器件, 从而研制成所谓的全超导接收机, 那将会极大地降低整个系统的噪声系数、增加系统集成度从而降低尺寸和功耗. 所以, 近几年有多个研究组致力于全超导接收机的研究工作.

高温超导天线的研究是从高温超导体发现后不久就开始的. 同传统天线相比, 超导天线损耗非常低, 而且由于超导天线一般是片状微带形式, 所以其尺寸小且便于与后面的滤波器集成. 但是正由于超导天线的Q值高, 也带来了带宽窄的缺点. 所以近年来关于超导天线的研究主要方向是增大其带宽. 在2005年, 日本的一个研究组[74]报道了一款超导沟槽环状平面天线, 并将其与一个2阶的超导滤波器集成. 该天线尺寸只有4 mm×8 mm, 带宽达到3%. 2007年, 他们通过EM仿真软件进一步优化其天线和匹配电路, 使其尺寸最终减小到4.1 mm×1.9 mm, 且相对带宽增大到13%[75]. 另外, 阿尔及利亚康斯坦丁大学研究组[76~80]最近几年也针对提高超导天线的带宽做了大量工作.

高温超导振荡器和混频器是利用约瑟夫森结的非线性I-V效应来工作的, 其研究工作也是自高温超导材料发现后不久就开始了[81~83]. 最近几年, 澳大利亚的杜佳研究组[84~87]发明了一种新型的高温超导振荡/混频器, 图8(a)显示的是包含两个约瑟夫森结的高温超导振荡/混频器, 其芯片尺寸5 mm×5 mm, 封装后尺寸为5.2 cm×3.4 cm×1.2 cm[85]. 另外, 他们还设计了超导低通和带通滤波器[88], 并与高温超导振荡/混频器进行了集成(图8(b)), 从而得到了单芯片集成的全超导下变频接收机[89~92]. 实测结果表明该超导下变频接收机能在20~77 K范围内稳定工作. 在20 K下, 增益为–4.7 dB, 这是目前为止公开文献报道的超导混频器增益最高值[90].

3 高温超导滤波器的应用现状及进展

3.1 高温超导滤波器的移动通信应用

近几年移动通信迅猛发展的同时也带来了不少新问题, 比如频率资源越来越紧缺, 各家运营商不同制式之间相互干扰日益严重, 这就给高温超导滤波器及其接收前端的应用带来了良好契机. 高温超导

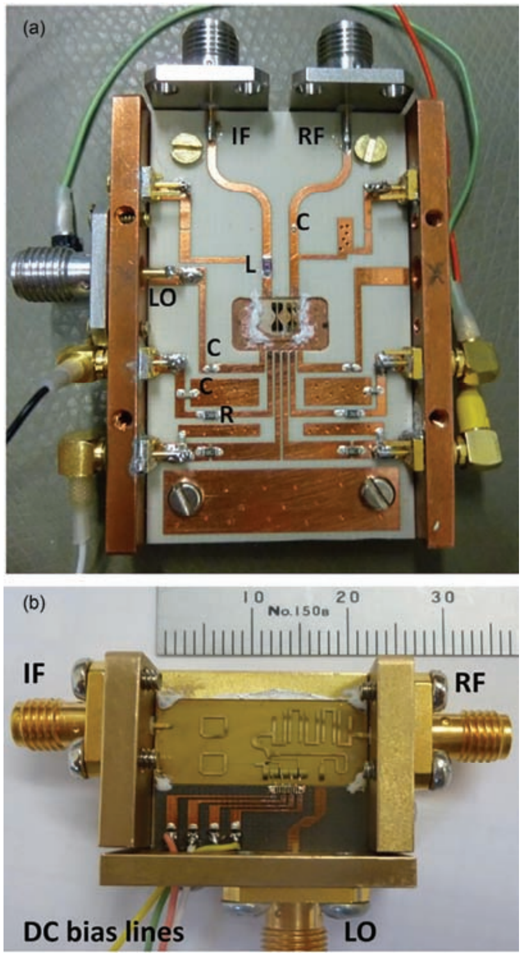

图 8 (网络版彩色)Bai等人[85]研制的包含两个约瑟夫森结的高温超导混频器(a)以及与超导滤波器集成得到的超导下变频接收机(Du等人)[91]

Figure 8 (Color online) (a) An HTS Josephson junction mixer by Bai et al.[85] and (b) an HTS Josephson down-converter integrated with HTS mixer and HTS filter (b) reported by Du et al.[91]

微波接收前端的低噪声系数可以提高微波接收机的灵敏度，灵敏度的提升意味着相同功耗下基站覆盖面积的增大．而高温超导微波接收前端的高选择性可以极大地提高基站的抗干扰能力，提高通话质量．

目前，高温超导微波接收前端在移动通信中应用最广泛的是美国．据美国超导技术公司(STI)宣称，有超过10000个基站使用了他们生产的高温超导微波接收前端(http://www.suptech.com/)，而且根据实际应用效果来看，使用高温超导微波接收前端可以使基站覆盖面积增大10%~15%．在欧洲也曾开展过超导通信系统项目[93,94]．

在中国，清华大学针对码分多址(code division multiple access，CDMA)通信标准研发了两通道的高温超导接收机[95]，每个通道都包含一个14阶的超导带通滤波器和低噪声放大器．该超导接收机首先在天津的一个CDMA基站进行了试验[96]，取得了良好效果．然后，在北京联通公司的5个CDMA基站中都安置了超导接收机，建成了超导通信示范小区，进行了实际运行(如图9所示)．18个月的运行结果显示，采用超导接收机后手机平均传输功耗降低了2.35 dB[97]，通话质量大大提高．天津海泰超导电子有限公司从2004年开始也在CDMA基站上进行了超导接收机的试应用，验证了其对于提高灵敏度和抗干扰能力的作用．时分同步码分多址(time division-synchronous code division multiple access，TD-SCDMA)通信标准是我国自主知识产权的移动通信制式，因为其发射端和接收端工作于同一频段，所以要求滤波器具有较高的功率承受能力．中科院物理所针对TD-SCDMA基站研制了功率承受能力达到11.7 W的高温

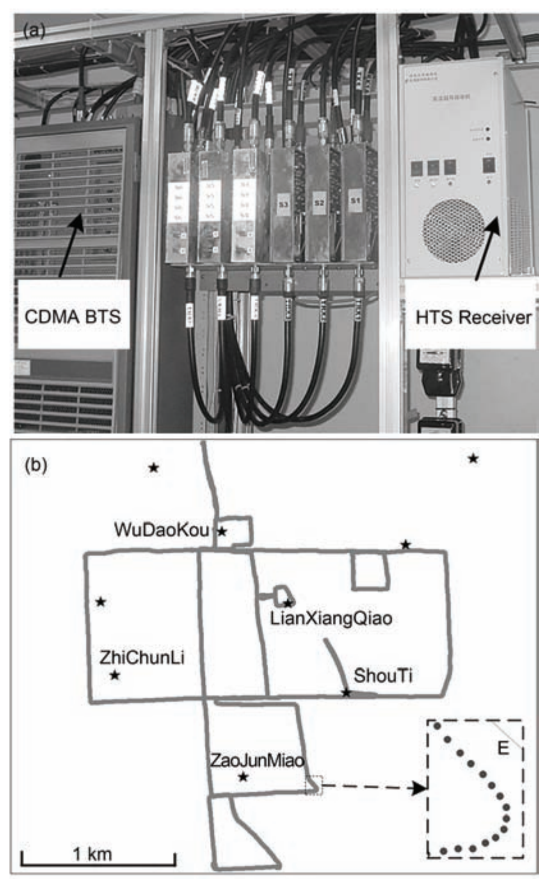

图 9 清华大学在北京联通公司的CDMA基站中安置超导接收机，建成了超导通信示范小区[97]

Figure 9 The photo of one CDMA BTS installed with one HTS receiver and HTS demonstration BTSs' locations and the drive test route[97]

超导滤波器[98], 开发出了世界首台用于TD- SCDMA的超导接收前端并进行了试应用[99]. 应用结果显示在强干扰环境下采用超导接收前端误码率降低了80%, 抗干扰能力提高了10 dB, 从而大大提升了通话质量.

在国家高技术研究发展计划(863计划)课题“高性能超导滤波器及示范应用”(课题编号: 2014AA032703)的支持下, 中科院物理所与合作单位共同研制了多台用于移动通信基站的超导滤波器前端系统, 并进行了挂网测试. 测试结果显示, 超导滤波器前端的性能稳定, 滤波效果明显优于普通滤波器, 安装超导滤波器前端后小区业务有一定提升, 小区间歇性指标恶化明显减少, 性能指标更加稳定.

由于目前的制作超导滤波器使用的高温超导材料仍需在液氮温度下工作, 上述实用高温超导前端均需要配备价格较为昂贵的机械制冷机, 因而在规模应用方面遇到了较大的挑战. 目前国内许多研究机构正在努力开发低成本、高性能的高温超导前端, 力求早日在移动通信基站的规模应用上取得突破.

3.2 高温超导滤波器的空间试验及应用

美国[100~102]、法国[103]、德国[104]、加拿大[105]、中国[106~108]和印度[109]等世界上多个国家都开展了适用于空间应用的高温超导微波器件的研制, 有的国家还完成了在轨测试和应用. 其中最早和影响最大的首数美国海军研究实验室(NRL)主导的高温超导空间实验计划(HTSSE). HTSSE计划共分三期, 其中第一期是高温超导微波器件的空间在轨测试, 第二期进行高温超导前端子系统的空间在轨测试, 第三期则是实际应用阶段. 见诸公开报道的HTSSE第二期于2000年完成, 各种高温超导微波器件和子系统共在太空进行了18个月的运行测试. 根据NRL的试验总结报告, 高温超导微波器件和子系统能够经受地面存储、火箭发射和在轨运行等空间环境, 其抗空间辐照能力比半导体器件高几个量级, 因而高温超导微波器件和子系统完全可以用于民用和军用卫星通信.

中国的高温超导空间试验起步于十几年前. 2005年, 中科院物理所完成了高温超导滤波器的地面模拟空间环境试验和与某型号卫星系统联机测试, 试验结果表明我国自主研发的高温超导滤波器能够经受空间力学环境试验的检验, 且通过采用超导技术使卫星接收机噪声温度降低73%[106]. 2012年10月14日, 由中科院物理所和中国航天科技集团公司510研究所共同研制的超导滤波器验证试验装置随实践九号卫星发射升空, 这是世界上继美国HTSSE后第二个成功的超导空间实验. 该高温超导空间实验装置包含一台国产斯特林制冷机和一个高温超导滤波器, 如图10所示, 目的是为了验证国产制冷机和超导器件能够在空间环境工作[107,108]. 2016年9月, 由中科院物理所研制的作为天宫二号有效载荷的实用高温超导微波接收前端成功发射升空, 截至目前运行状态良好.

3.3 高温超导滤波器的雷达应用

高温超导滤波器在雷达中应用的主要目的是消除各种邻频干扰信号[13,110~115], 其中最成功的应用是在气象雷达中. 中科院物理所曾首次将高温超导微波前端引入风廓线雷达中, 并取得了良好效果[13]. 该风廓线雷达工作于1320 MHz, 通过发射并探测返回的微波信号来测定空中风向和风速. 由于移动通信信号的不断增多增强, 该雷达遇到了严重的邻频干扰问题, 经常误测误判, 严重时甚至导致雷达瘫痪. 中科院物理所研制了一款带宽5 MHz, 中心频率1320 MHz的高陡度滤波器, 并和一个低噪放、一台小型制冷机一起组成超导微波前端, 实验室测试结果表明该超导前端不仅可以提高雷达抗干扰能力达48.4 dB, 而且还可以使雷达接收机灵敏度提高3.8 dB[111]. 然后超导微波前端被置于雷达接收机前端替换雷达原

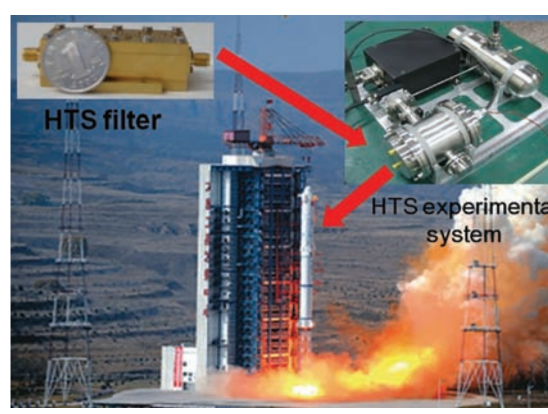

图 10 (网络版彩色)2012 年 10 月 14 日, 超导滤波器验证试验装置随实践九号卫星发射升空. 该超导滤波器验证试验装置包含一台国产斯特林制冷机和一个高温超导滤波器[108]

Figure 10 (Color online) First HTS space experiment for HTS filter in China was successfully carried out on orbit since October 14, 2012. Inset is the picture of the HTS filter and space experimental system[108]

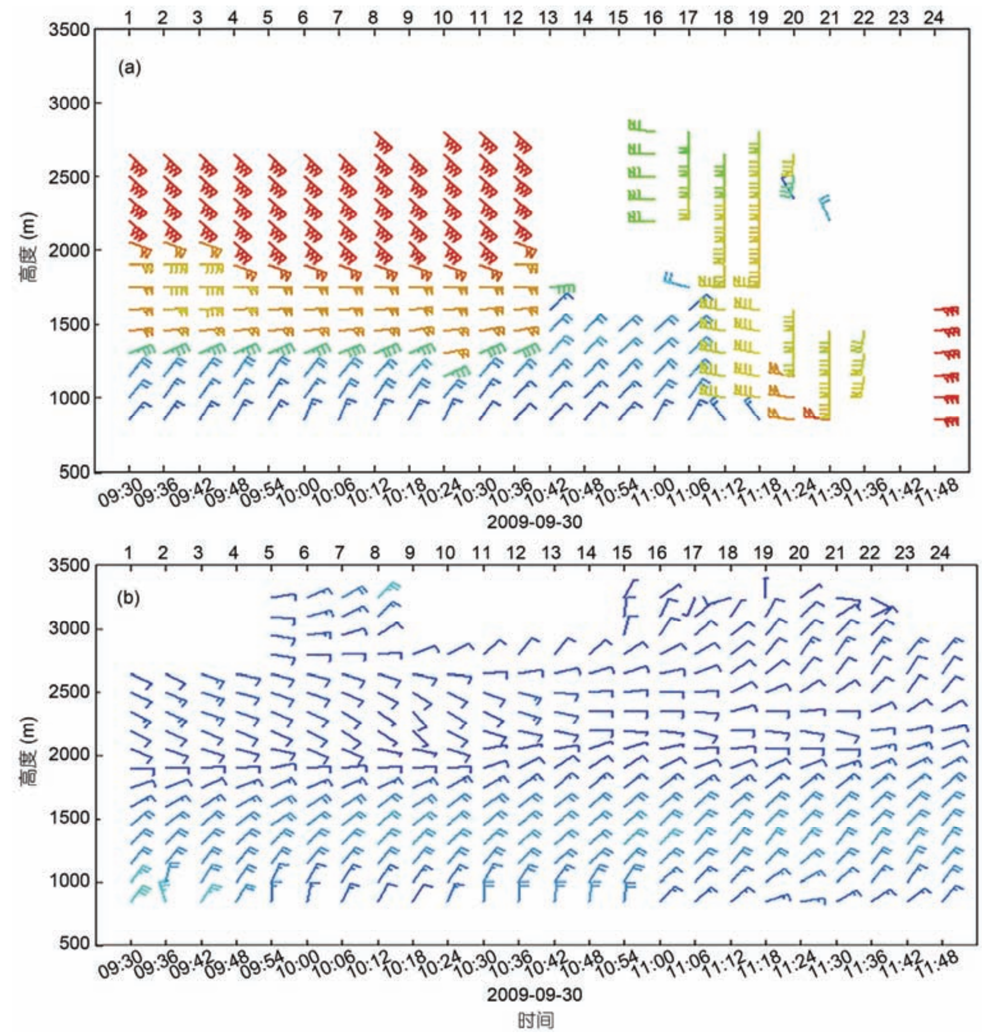

图 11 (网络版彩色)风廓线雷达测得的风廓线, 图中图标表示风向与风力. (a) 在干扰严重的情况下未使用超导前端时不能正确测量风廓线; (b) 使用超导前端测得的风廓线[112]

Figure 11 (Color online) Comparison of wind profiles measured on September 30, 2009, using conventional (a) and HTS (b) wind profilers. The horizontal axis denotes the time, and the vertical axis denotes the height[112]

有低噪放进行试运行. 实际应用结果表明在干扰信号强烈以至于传统雷达无法正常工作时, 采用超导前端的雷达还能正确探测风廓线信号(如图11所示)[112].

东芝公司曾针对气象雷达研制了既可用于接收端又可用于发射端的超导滤波器[113~115]. 因为超导材料很难承受大功率微波信号, 东芝公司的滤波器采用了腔体滤波器加超导谐振器的混合结构, 使得发射信号通带内中心频率附近的信号从腔体滤波器通过, 而发射信号通带边缘的信号从超导谐振器通过. 由于大部分信号功率集中在通带内中心频率附近, 通过超导谐振器的信号功率大约是腔体滤波器的1/1000. 于是, 这样的混合结构滤波器既能承受雷达发射的大功率信号, 又在带边具有很好的陡度.

东芝公司还为相控阵雷达研制了包含16个发射通道和16个接收通道的超导多通道微波前端T/R 模块[116,117]. 其中16个接收通道中每个通道都包含一个超导滤波器和一个低噪放, 16个接收通道集成在一个100 mm×100 mm×36.5 mm的真空室内, 由一台制冷机来制冷. 超导多通道微波前端T/R 模块不仅展示出很低的噪声系数(噪声温度小于60 K), 而且还具有良好的幅度平坦度和相位线性度.

3.4 高温超导滤波器在天文和深空探测中的应用

天文探测中遇到的都是非常微弱的信号, 天文

望远镜的微波接收机需要具有非常优异的探测灵敏度，它们对于通信雷达等干扰信号尤其敏感，所以射电天文望远镜一般建造于人迹稀少的郊野地区．但是近年来随着广播电视和通信工业的蓬勃发展，射电天文望远镜遇到了越来越严重的干扰问题．高温超导滤波器具有非常小的插入损耗和非常高的带外抑制，正是解决射电天文望远镜干扰问题的最佳手段．而且因为射电天文望远镜的微波接收机为了降低噪声系数，本身已经引入了制冷机来给低噪放降温，所以引入高温超导滤波器时不需要额外增加制冷机，从而大大节约了引入时的成本．英国伯明翰大学曾经针对英国的Jodrell Bank射电望远镜[118~122](图12)和多天线微波连接干涉仪网(Merlin)[123]研制过多款超导滤波器．例如，针对Jodrell Bank射电望远镜遇到的605.25和615.25 MHz处的严重电视信号干扰，伯明翰大学研制了一款通带607~613 MHz的8阶准椭圆函数滤波器，其带内波纹0.1 dB，最大插入损耗0.3 dB，而带外抑制高达85 dB．安装该滤波器后，605.25和615.25 MHz处的干扰信号被成功滤除．

在国内，中科院物理所首先开展了针对射电天文望远镜的高温超导滤波器研制[2,124]．针对密云天文站射电天文望远镜研制的宽带高温超导滤波器插入损耗只有0.05 dB．中国电子科技集团第16研究所针对嫦娥探月计划也研制过多款高温超导滤波器，并计划继续在中国的深空探测基站中应用更多的高温超导滤波器．

4 总结

在过去二三十年间，人们对高温超导滤波器的研究倾注了巨大努力并取得了巨大进展，研制出了一大批具有极小插入损耗、高带边陡度、高带外抑制、极窄带宽以及较高带内群时延平坦度等优异性能的高温超导滤波器，并在移动通信、雷达、空间卫星及天文探测等领域取得了良好应用效果．最近几年，关于高温超导滤波器的研究又开拓了大功率承载能力滤波器、可调频率超导滤波器、多通带超导滤波器和全超导接收机等新的领域并取得了可喜进展．

图 12 (网络版彩色)英国的Jodrell Bank射电望远镜
Figure 12 (Color online) The Jodrell Bank Radio Observatory in UK

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Summary for "高温超导滤波器及其应用研究进展"

The high temperature superconducting filters and its application progress

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Microwave filters are essential elements in many areas of RF/microwave engineering. The crowded frequency spectrum has put forward higher requirements on channel filters. Not only very high close-to-band rejections are required to prevent interference to or from closely neighboring channels, but also very low insertion loss is required to reduce system noise figure. Some RF/microwave system require in-band group-delay and amplitude flatness to minimize signal degradation even further. Surface resistance of high temperature superconducting (HTS) material is about 1000 times less than the best conventional metals such as copper and silver at microwave frequency. So a significant effort has been put into the research and realization of high performance microwave HTS filters since the discovery of HTS materials. HTS microwave filters with remarkably high performance have been constructed in the past 30 years. For example, by selecting appropriate resonators with high quality factors and employing well-designed coupling structures with week coupling coefficients, some HTS filters can have fractional band width (FBW) blow 0.1% with very high selectivity. The insertion loss of some HTS filters can be as low as 0.05 dB. With above excellent performance, HTS filters can not only eliminate unwanted interference but also minimize noise figure of the microwave system. HTS filters and their front-end subsystems have also been successfully applied to many fields and brought multiple economic returns and social benefit. It is reported that HTS receiver front-end subsystem, which integrate with narrow-band highly selective HTS filters and low noise amplifiers (LNA) in a cryocooler, has been employed in more than 10000 base stations in America. According to the promotion materials, the ultra-low-loss and high sensitivity of the HTS receiver can translate into 10%–15% or more increased base station coverage area and data throughput. In some cases carriers could add 8% or more usable resource blocks and capacity due to the high selectivity of the HTS receiver, valued at hundreds of millions of dollars. Design technology of HTS filters has been developed rapidly at an incredible speed. In recent years, many efforts have concentrated on novel HTS filter design technologies, including those in high power handling capability filters, multiplexer or multiband filters and frequency tunable filters. Some research groups are trying to develop all-HTS integrated microwave front-end receivers, which integrate HTS filter, oscillators, mixers and antenna into a whole chip. The all-HTS integrated front-end receiver could make the system compact, efficient, and be able to exploit the full potential of the superconductive components. In this paper, the research status, trend of development and application progress about HTS filters are reviewed. The best performances of HTS filters ever reached in specifications such as insertion loss, FBW, out of band rejection, skirt slope and in band group delay are firstly reviewed. Then the remarkable progress in the most recent years which stand for the research trends of HTS filter technology is presented in detail. At last the application of HTS filters and their front-end subsystems to mobile communications, space or satellite communication technology, radar detective system, deep space detection and radio astronomy is also reviewed.

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