A Thirty-year History of Superconducting Microwave Devices and Fundamental Studies Thereof

Shigetoshi Ohshima
Yamagata University, Jonan 4-3-16, Yonezawa 992-8510,

ohshima@yz.yamagata-u.ac.jp

Abstract. Thirty years have passed since the discovery of high-temperature superconductors (HTS), and practical applications of HTS equipment and devices are moving into full-swing. From the beginning of their discovery, the use of HTS in microwave devices has been recognized as one of their most practical applications. This is because the surface resistance of HTS is about 1/1000 of that of pure copper at 1 GHz and 77 K. From early on, researchers have recognized that high performance of microwave passive devices could be realized by utilizing the characteristics of HTS. In addition, the size of HTS microwave devices is relatively small, and they can be cooled by a small cryocooler. Furthermore, we were able to establish high-quality HTS thin-film fabrication technology essential for producing high performance microwave devices in a short period of time. In view of the above, I would like to present an overview of the past thirty years of superconducting microwave devices and fundamental studies thereof.

1. Introduction
High-temperature superconductors (HTS) were discovered over thirty years ago and since then, their superconducting applications have been used in various fields. Their practical uses include bandpass filters, microwave kinetic inductance detectors (MKIDs) and transition edge sensors (TES). In this paper, we review the thirty-year history of HTS and discuss the following topics.
(1) Superconducting properties needed for high performance microwave superconducting devices
(2) Topics concerning superconducting microwave devices reported so far
(3) Practical use of superconducting bandpass filters
(4) Superconducting microwave devices expected in the future

2. Superconducting properties needed for high performance microwave superconducting devices
The most important superconducting property necessary for realizing high performance microwave devices is surface resistance ($R_s$). $R_s$ is defined as the ratio of the electric field ($E$) and the magnetic field ($H$), $R_s = E / H$, when the conductor is irradiated with electromagnetic waves. Since superconductors have very low electrical resistance at frequencies below microwave frequency, their $R_s$ is quite small compared to normal metals. The temperature dependent $R_s$ of Al and Cu films and YBa$_2$Cu$_3$O$_y$ (YBCO) films are shown in Figure 1. The $R_s$ of YBCO thin films in the superconducting state at 1 GHz is approximately three orders smaller than that of Cu and Al thin films. This low $R_s$ is the driving force for high performance and miniaturization of microwave superconducting devices. The $R_s$ of superconducting thin films is small even in the magnetic field. Figure 2 shows the relationship...
between the applied magnetic field and the $R_s$ of YBCO films. $R_s(90)$ and $R_s(0)$ indicate the surface resistance when the magnetic field is applied normal and parallel to the film plane, respectively. $R_s$ of YBCO films in a high magnetic field is quite smaller than that of pure Cu films [1-3]

![Figure 1. Temperature dependent $R_s$ of Al, Cu and YBCO films](image)

![Figure 2. Applied magnetic field dependent $R_s$ of YBCO, and Cu films](image)

### 3. Topics concerning superconducting microwave devices over the past thirty years

#### 3.1. Electrical small antenna

The first focused microwave device to be developed when HTS were discovered was an electrical small antenna. The electrical small antenna was cooled with liquid helium had a high gain and high directivity [4]. More practical applications would be possible if the electrical small antenna could be made with HTS, which could maintain a superconducting state with liquid nitrogen. Liquid nitrogen is easier to handle than liquid helium. Itoh et al. made an electrical small helical antenna with Bi-2223 wire and demonstrated that it had high gain and high directivity [5-6]. A helical antenna, however, cannot be cooled by a small refrigerator and that is a serious problem for practical use. Patch antennas can be cooled by a small refrigerator and many researchers have investigated various types of patch antennas [7-9]. Ehata et al. investigated an array square-patch antenna and mini-refrigerator for patch antennas [10]. According to their experimental results, the superiority of the superconducting antenna could be demonstrated, but it could not be put into practical use. This was due the disadvantage that superconducting antennas must be cooled to a low temperature.

#### 3.2. Superconducting bandpass filters for wireless communication

Superconducting bandpass filters have advantages compared to conventional filters, such as (1) large out-band rejection, (2) strong frequency selection and (3) low insertion loss. In the late 1990s, as the spread of wireless communication rapidly increased in the United States, deteriorating quality of communication was a big problem. This is because the usual band pass filter failed to distinguish the frequency bands of the companies. It was found that the quality of speech in mobile-phones was improved significantly by using an HTS filter and superconducting base stations have spread rapidly in the United States [11-12]. Although the use of a superconducting bandpass filters was also studied in
the third generation wireless communication system IMT-2000 [13-16], unfortunately, the superconducting bandpass filter system was not adopted because of its high price.

The next target of practical application for superconducting bandpass filters was software communications. Software wireless communication that can share facilities in the base station is an attractive next generation wireless communication method. It was important to develop a filter capable of shifting the resonance frequency in a short time. Several techniques for shifting the center frequency of the superconducting bandpass filters have been proposed [17-20]; however, the most practical method is to use a tuning rod. Ohshima et al. developed an automatic tuning system using dielectric rods. Figure 4 shows a picture of the apparatus. They could shift the center frequency of the bandpass filter in a very short time, less than 0.5 seconds as shown in figure 5. [21-22].

![Figure 4. Automatic tuning system for HTS bandpass filter.](image)

**Figure 4.** Automatic tuning system for HTS bandpass filter.

**Figure 5.** Center frequency shift of HTS bandpass filter using automatic tuning system shown in Fig. 4

4. Practical application of HTS bandpass filters

Several superconducting bandpass filter systems have already been put to practical use besides cellular phone base stations. Here, we show three applications: (1) reduction of city noise for radio astronomy, (2) ultra-narrow bandpass filters for weather radars. (3) ultra-wide band filters for UWB communication. UWB-communication filters are not yet practically used; however, in the future, practical use is possible. The three types of superconducting bandpass filters are introduced below.

4.1 Reduction of city noise for radio astronomy

It is necessary to receive weak radio waves coming from outer space with high sensitivity at radio astronomical observatories, which are usually installed at the top of a high mountain or in desert areas. However, it may be necessary to install such a system in the city. Kashima Space Research Center installed a radio telescope of 34m and received a weak cosmic radio wave. When third generation wireless communication became widespread, noise in the mobile phone frequency band was superimposed on weak radio waves coming from outer space and cosmic radio waves could not be observed. Therefore, it was necessary to use superconducting bandpass filters with high out-of-band cutoff characteristics. By installing superconducting bandpass filters in front of the pre-amplifier of a radio wave telescope, noise from the wireless communication base station could be removed [23-24]. A similar problem was raised in world radio telescopes installed in cities. Figure 6 shows the experimental data of the removal of city noise using a superconducting bandpass filter system [25]. Mobile noise and Wi-Fi noise could be removed by using the superconducting filter.

![Figure 6.](image)
4.2 Ultra narrow bandpass filters for a weather radar

The insertion loss and skirt characteristics of the bandpass filter depend on the $R_s$ of the films used, but they also affect the bandwidth of the filter. As the bandwidth decreases the insertion loss increases if the $R_s$ of the film is not small enough. In Japan, to secure the frequency of the rapidly increasing wireless LAN networks, the frequency band of weather radar have been narrowed. The problem here is the magnitude of the receiving signal. Since the power transmitted from the weather radar exceeds several dozen kW, the receiving signal may also be large; however, the power tolerance of the superconducting bandpass filter is less than 10 W. Therefore, ingenuity is necessary. Toshiba group has created the circuit as shown in figure 7 [27]. The same frequency radio waves as the transmission power do not pass through the superconducting bandpass filter and only weak signal waves with slightly shifted frequency can pass through. Through such a circuit, they could construct a highly sensitivity weather radar system.

4.3 Ultra-wide band filter for UWB communication

The necessity of ultra-high speed communication has been increasing year by year and various methods are being studied. Among them, UWB communication using an ultra-wide band filter is suitable for ultra-high speed communication in a limited space and future progress is expected. Fig. 8 shows the schematic figure of the frequency band and radiation power of W-CDM, GSM and UWB communication. UWB communication has a small power transmission and wide frequency band. Superconducting bandpass filters are suitable for this type of communication and are being examined throughout the world. We also examined the superconducting bandpass filter for UWB communication. There are two frequency bands for UWB communication in Japan: 3.4 - 4.8 GHz (lower band) and 7.25 - 10.25 GHz (higher band). Fig. 9 shows the structure of a UWB superconducting filter for low band, and Fig 10 shows the results. The filter meets the specification of UWB communication [28].
5. Prospective microwave superconducting devices

There are several superconducting microwave devices besides the bandpass filter. Among them, NMR pickup coils and MKIDs for terahertz wave detection are close to being put into practical application.

5.1 NMR pickup coils: Although nuclear magnetic resonance (NMR) is fundamentally not very sensitive, improvement of sensitivity is important and is being vigorously studied in the United States [29-30] and Japan [31-32]. Equation (1) shows the S/N of an NMR system, where, $Q_L$, $T_{eff}$, $T_R$ and $\eta$ are the quality factor of the coil, effective sample temperature, pre-amplifier temperature and filling factor of coil, respectively. It is important to increase $Q_L$. To increase $Q_L$, the $R_s$ of the pickup coil material must be small. As shown in Fig. 2, the $R_s$ of the superconducting thin film is more than two orders of magnitude smaller than the usual metal even in a high magnetic field. Therefore, it is important to examine a superconducting pickup coil to improve NMR sensitivity. Fig. 11 shows a schematic drawing of the NMR superconducting coil. As shown in this figure, we use a 2 flats coil.

$$ S/N \propto \frac{\eta Q_L}{T_{eff} + T_R} $$

Figure 12 shows the input power dependence on $Q_L$ of the NMR superconducting pickup coil. The applied magnetic field is 14.1 T and the resonance frequency is 800 MHz. The value of $Q_L$ is over 15,000 with a low input power and the value decreases with increasing input power. The value of $Q_L$ for the
superconducting pickup coil is about fifty times the $Q_L$ of the room temperature copper wire coil. Therefore, if the superconducting pickup coil is used, NMR sensitivity can be improved.

![Figure 11. Schematic drawing of NMR superconducting pickup coil](image)

**Figure 11.** Schematic drawing of NMR superconducting pickup coil

![Figure 12. Input power dependence on $Q_L$ of the NMR superconducting pickup coil](image)

**Figure 12.** Input power dependence on $Q_L$ of the NMR superconducting pickup coil

5.2 **MKIDs of terahertz wave detection**

In recent years, it has become important to observe the electromagnetic waves of submillimeter waves coming from outer space in order to elucidate the creation of the universe. Several methods of detecting submillimeter radio waves have been proposed, but recently MKIDs have been shown to be a useful device to detecting such waves. An MKID is an element combining an antenna for receiving a submillimeter - terahertz wave and a resonator for resonating at $\sim$ GHz. Figure 13 shows the schematic drawing of the frequency shift of an MKID after receiving a submillimeter wave. By observing this frequency shift, it is possible to do wide-band detection from submillimeter wave to terahertz wave. The advantage of this element is that: (1) we can observe submillimeter waves to terahertz waves by evaluating the resonance in the microwave range, (2) it is easy to realize an array beyond 500 elements. Studies for the development of MKIDs are currently spreading around the world. Figure 14 shows a photograph of the MKID array reported by the Otani Group at RIKEN [33-34]. The MKIDs were fabricated of a high quality Al film prepared by the MBE method. They will be put into practical use shortly.
6. Summary

In this paper, we reviewed the thirty-year history of superconducting microwave devices, introduced practical uses of superconducting bandpass filters in recent years and discussed how superconducting NMR pickup coils and MKIDs for terahertz wave detection are expected to be put to practical use in the future. In addition, it is important to use a low Rs superconducting film to realize a high performance superconducting microwave device. It was shown that the Rs of c-axis oriented YBCO films is experimentally found to be three orders of magnitude smaller than that of thin metal films in both a non-magnetic field and a magnetic field of around 1GHz. We are expecting further applications of superconducting microwave devices in the future.

Acknowledgement

In summarizing this paper, we would like to show appreciation to the following people: Prof. B.S. Cao of Tsinghua Univ. in China, Dr. Kayano of Toshiba Corporation, Dr. Otani of RIKEN. Q of the NMR superconducting pickup coil in the magnetic field was measured by Mr. Tsuji of JEOL RESONANCE, Co, Ltd. English grammar was checked by Prof. Matthew Zisk of Yamagata University.

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