HIGH-TEMPERATURE SUPERCONDUCTORS AND MM WAVE TECHNOLOGY: A CHALLENGE AND PERSPECTIVES

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Introduction.

Regarding the general potential of high-temperature superconductors (HTS) for applications in passive microwave (MW) devices and systems, there are a number of excellent reviews and books (see for example [1-4] and others). However practically all the authors did not touch the question concerning prospects of HTS-based passive components in millimeter (mm) wave range. As a rule developments of MW components are carried out in a direction of gradual shorting of wavelength i.e. in direction of mm wave range. Because the main advantage of superconductors contrary to normal conductors decreases with shorting of wavelength, the problem arises concerning determination or at least evaluation of the upper frequency boundary where advantages of HTS-based separate devices and systems in a whole remain else. In the present work an attempt is made to have analyzed potential of HTS and to search attractive areas of HTS-based component application in mm wave range.

Impedance properties of HTS films and potential of their improving for mm wave range.

The concept of the surface impedance Z_s makes easy the description of electrodynamics at the boundary between vacuum and the surface of a conductor or superconductor. In the local limit

$$Z_S = \sqrt{i\omega\mu_0/\sigma} = R_s + iX_s\,, \tag{1}$$

where σ is the complex conductivity, $\sigma = \sigma_1 + i\sigma_2$, $\omega = 2\pi f$, f is the frequency, R_s and X_s are the surface resistance and reactance. In the limiting case for superconductor when $\sigma_1/\sigma_2 << 1$ one can obtain

$$R_s = \omega^2\mu_0^2\sigma_1\lambda^3/2 \text{ and } X_s = (\omega\mu_0/2\sigma_2)^{1/2} = \omega\mu_0\lambda\,. \tag{2}$$

For a normal conductor from (1):

$$R_s = X_s = R_n = (\omega\mu_0/2\sigma_1)^{1/2}\,. \tag{3}$$

Knowledge of the frequency dependence of the surface impedance is especially important for evaluation of potential MW applications of HTS. Some data for high-quality epitaxial $YBa_2Cu_3O_{7-\delta}$ (YBCO or Y-123) films at T=77K are cited in [2-4]. The advantage of the epitaxial films compared to Cu is seen clearly. YBCO films show a lower R_s compared to Cu to about 200 GHz. Data for Tl-2212 are better at 77K about a factor 2 than the data on YBCO films due to the higher T_c (106 K). From (2) and (3) one can determine maximum benefit (merit) due to HTS application

$$m = \frac{R_s^{(Cu)}}{R_s^{(HTS)}} = \frac{\sqrt{2}}{\sqrt{\sigma_n^{Cu}}\,\sigma_n^{HTS}\lambda^2}\frac{1}{\omega^{3/2}} = \left(\frac{A}{f}\right)^{3/2}. \tag{4}$$

From determination of critical frequency f_c as a frequency at which m=1, one can find A=f_c. Thus

$$m = (f_c/f)^{3/2}\,. \tag{5}$$

Dependence m versus f is presented in Fig.1 for Y-123 at T =77 K (f_c=200GHz). Unfortunately m decreases with frequency with exponent 3/2.

Evidently, for a given value of f_c a certain boundary frequency f_b exists at which value of m is already insufficient for achievement of advantage that has technologic or economic importance. With growth of f_c at given frequency a value of m increases also or f_b increases at given m (see Fig.1). Unique way to enhance m is reduction of surface resistance R_s of superconductor. Prospects of improvements of HTS R_s are as follows: 1) new materials with higher T_c; 2) reduction of operating temperature T; 3) use of some technological approaches for optimizing MW properties. Consider briefly items 1) to 3).

1). There are about 40 different HTS compounds which have been studied [2]. Most of them are less suitable for MW applications than Y-123. To the most known HTS subsystems belong the $Tl_2Ba_2Ca_nCu_{n+1}O_y$ (Tl-2212, T_c=108 K; Tl-2223, T_c=127 K) compounds with higher T_c in comparison with Y-1123. The Tl films provides between 40 and 70 K values of R_s about a factor 2 lower than Y-123 at the same temperature but suffer from granular effects which can cause nonlinear MW phenomena. Y-123 still presents the most thoroughly investigated and most frequently adopted HTS material for MW applications and Tl-2212 is well-established alternative.

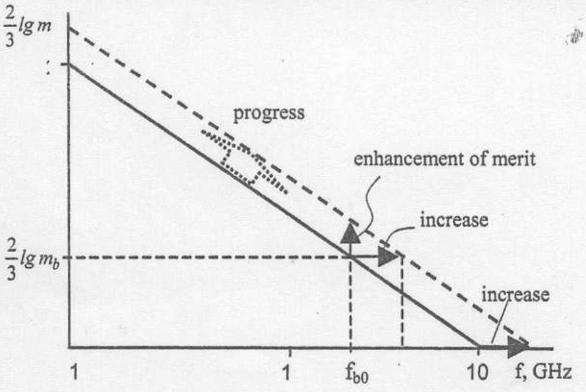

Figure 1. Dependence of merit of HTS-based microwave element on frequency.

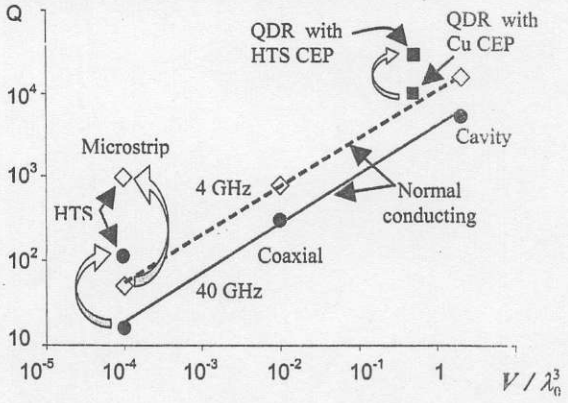

Figure 2. Dependence of unloaded Q of resonators in different technology on parameter V / λ_0^3.

2). Refrigeration is a major problem for all of superconducting devices and without exception. The unique benefits of the HTS-based devices and subsystems are more clearly when operating temperature becomes lower. On the other hand, the efficiency of cryocoolers increases with temperature. Therefore, the acceptance of cryogenic devices depends on a sensitive balance between total system performance and not economic efficiency [2]. The eigen quality factor Q_o can be considered as typical factor of merit (FOM). Small weight and volume are of major benefit at application of HTS MW devices especially in satellite-based systems. The benefit of miniaturized and / or high-performance HTS circuits must not be compensated by bulk or heavy refrigerators. Such counter balance is likely to prevent HTS devices from being applied. Therefore, earth-basing devices in mm wave range are more perspective than devices of board appointment because for the former a cryocooler weight is not such critical as for the latter. Reduction of wavelength causes decrease of linear dimensions of HTS-based devices in proportion of wavelength which must result of decrease of thermal load of closed-cycle cooler. In this connection decrease of cost must take place. One can note that decrease of T from 77K to 60K results decrease of Rs about a factor of 2 [2, 3].

3). It is important to minimize R_s and to improve the power handling capability of the films produced now. Here, there are several ways. Low surface resistance and linear MW response up to high amplitude were observed in coevaporated films up to 700 nm in thickness [2]. Above mentioned increase of the film thickness gives decrease of Rs about a factor 2. Recently the article [5] had informed about so-called Pa-MOCVD technique for growth of μm-thickness high-quality Y-123 films with single-crystal-like structure. However microwave characterization of those films was not carried out. Experimental data on comparative study of Dy-123 and Y-123 sputtered onto $LaAlO_3$ substrates showed that $R_s^{Y-123} / R_s^{Dy-123} \cong 1.6$ (at 10 GHz and 77K) [6]. In addition, it seems to be possible to decrease somewhat R_s by using artificial defects [7]. The effect of improvement was especially appreciable for Y-123 films on sapphire (about 20%) but its frequency dependence is unknown.

If to account all the real possibilities of decreasing R_s one can approach enhancement of m in per-unit as follows: (i) application Tl-2212 or Dy-123 films with use of some technological approaches gives factor of 2; (ii) reducing temperature from 77K to 60 K gives factor of about 2 and (iii) growth of the film thickness twice as large gives enhancement factor of 2 also. Thus, one can predict integral increase of m factor of 8. It follows that in principle one can expect increase of boundary frequency f_b factor of $n^{2/3} = 4$ at given m. Consequently, if to evaluate a present boundary frequency as f_{b0}=10GHz, the potential value f_b is f_{bp}=40GHz. This implies that at least Ka-band is potential attractive waveband for development of passive HTS-based components. Here power handling capability we do not consider for the present.

Fundamentals of passive HTS-based mm wave components. Candidates for applications.

The fundamental features of HTS are small value of Rs up to mm wave range and independence of MW field penetration depth on frequency up to the THz range. These features are important for designing low loss and/or nondispersive MW devices. Here in application to mm wave range a problem of miniaturization is absent or not pressing in comparison with a classic MW range. It is worth to underline also that some problems, which take place in centimeter wave band, are redoubled in mm range. They are appearance of spurious modes and high sensitivity to fabrication tolerances.

MW resonator is a simple component that can take advantage of HTS low R_s to achieve high-Q values. According to the configurations, resonators can be divided into three types, namely, one-, two- or three-dimensional resonator. HTS materials were used for making resonators of all three types [8]. Using the approach developed by Chaloupka [3] one can present dependence of unloaded Q of resonators in different technology on parameter V/λ_0^3 (V is volume of the resonator and λ_0 is free-space wavelength) for two frequencies, namely 4 and 40 GHz (Fig.2). This implyies: i) at decrease of resonator volume a value Q_o drops in a linear fashion at rise of frequency; ii) Q_o-factor decreases with frequency at the constant ratio of V/λ_0^3; iii) Q-factor of QDR with HTS conducting end-plates [9] exceeds Q-factor of cavity resonators at some less dimensions of the former.

Consideration of linear passive multiports allows one to obtain expression [3]

$$P_{diss}/P_{in} = \omega\tau/Q, \tag{7}$$

where $P_{diss} = \omega W/Q$, $W = \tau P_{in}$ is stored energy, P_{in} is input power, τ is group delay. One can see from (7) that components with large frequency-delay-product are candidates for HTS application. Loss increases with increase of τ. In addition, situation thickens with frequency, therefore only enhancement of Q-factor can compensate a growth of $\omega\tau$. In frequency band up to 40 GHz the most radical approach here is use of HTS materials, at f>40 GHz – cooling MW components made of normal metals and dielectrics. Therefore the candidates for HTS applications in mm wave technique are the same as in classic MW range, i.e. filters, resonators for oscillator stabilization, delay lines. Here HTS allow one to design mm components with performance which are inaccessible by using conventional technologies. It should be important to determine benefit of HTS technology on the subsystem level especially in mm area because conversation of superior component performance into system benefits will take place provided decrease of benefit with frequency.

Now it is not simply to predict the most challenging areas of HTS-based component application in mm wave range. However now one can eliminate a number of directions where these devices can be applied or already are applied: (1) low-noise cooled receivers with preselector in front-end; (2) resonators for oscillator stabilization (Hakki-Coleman QDR with HTS CEP); and (3) QDR with CEP for physical experiments (HTS impedance measurements [10], characterization of dielectrics at cryogenic temperatures [11]). Possibly, HTS-ferroelectric - or HTS-MEMS - based frequency-agile resonators and HTS-based delay-lines can be competitive in mm wave range also.

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