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Superconducting small antenna combined with a bandpass filter

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Abstract

A superconducting slot antenna combined with a bandpass filter composed of coplanar waveguide meanderline resonators has been designed and tested. Based on a new design theory for broadband impedance matching circuits, we designed a slot antenna with a small radiation resistance of 1 Ω impedance matched to a three-pole Chebyshev bandpass filter with 10 GHz center frequency and 0.35% fractional bandwidth. Experiments with a YBCO slot antenna on a MgO substrate have demonstrated the designed performance.
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Keywords: Superconducting microwave device; Slot antenna with bandpass filter; Superconducting antenna

1. Introduction

Intensive studies have been made of applications of high T_c superconducting thin films, which have extremely low surface impedance at microwave frequencies, to high performance microwave passive devices such as filters, resonators and antennas. Among them, the miniaturization of the superconducting antennas by taking advantage of the low-loss property of superconductors is desired [1–3], which is expected to lead to fully integrated microwave receivers. In our previous paper [4], we proposed a new design theory for the broadband impedance matching circuit for the small antenna, which is based on the conventional design theory of n-pole bandpass filter [5]. It was shown that the proposed matching circuit for the antenna acts as a bandpass filter for the antenna.

In this paper we designed and tested the slot antenna combined with a bandpass filter based on the new design theory. Performances of the slot antenna with the impedance matching circuit designed with the present theory are studied by the electromagnetic wave simulator. It is shown that the antenna with the small radiation resistance of 1 Ω was able to be matched to the external circuits with 50 Ω source resistance by using this matching circuit. The prototype miniaturized practical device, which integrates the slot antenna and the meander coplanar waveguide (CPW) transmission line resonators [6] within 15 mm × 15 mm dimensions, was fabricated by a YBCO thin film on a MgO substrate and it performance was confirmed by the experiment.

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2. Design of the small antenna with a bandpass filter

According to Ref. [4], the equivalent circuit for the small antenna with the impedance Z_a combined with a bandpass filter is shown in Fig. 1, where the formulas for admittance inverters are given by

$$
\begin{aligned}
J_{0,1} &= \sqrt{w}\sqrt{\frac{b_1}{Z_0 g_1}},\\
J_{i,i+1} &= w\sqrt{\frac{b_i b_{i+1}}{g_i g_{i+1}}}, \quad (i = 1, 2, \ldots, n-2)\\
J_{n-1,n} &= w\sqrt{\frac{b_{n-1} b'_n}{g_{n-1} g_n}},\\
J_{n,n+1} &= \sqrt{w}\sqrt{\frac{b'_n}{R_a g_n}},
\end{aligned}
\tag{1}
$$

with

$$b'_n = \frac{b_n}{1 - \frac{w x_a}{R_a g_n}},$$

where g_i $(i = 1, 2, \ldots, n)$ are normalized values for L, C elements for prototype lowpass filter given in [5], $w = (\omega_2 - \omega_1)/\omega_0$ is the normalized bandwidth, ω_1 and ω_2 are cutoff frequencies, $\omega_0 = (\omega_1\omega_2)^{1/2}$ is the center frequency, B_i $(i = 1, 2, \ldots, n)$ are the susceptance of the parallel resonance circuit given by

$$B_i = b_i\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right), \tag{2}$$

where $b_i = (\omega_0/2)(\partial B_i/\partial\omega)|_{\omega=\omega_0}$ $(i = 1, 2, \ldots, n)$ is the susceptance slope parameter, and we assume that $Z_a = R_a + jX_a$, and that in the vicinity of resonance frequency ω_0 the antenna reactance X_a can be expressed as

$$X_a = x_a\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right), \tag{3}$$

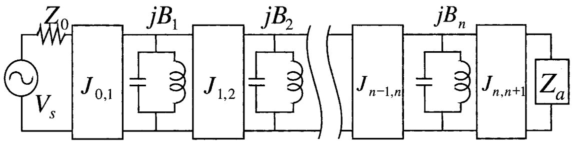

Fig. 1. The equivalent circuit for the antenna combined with the n-pole bandpass filter, where Z_a is the antenna impedance.

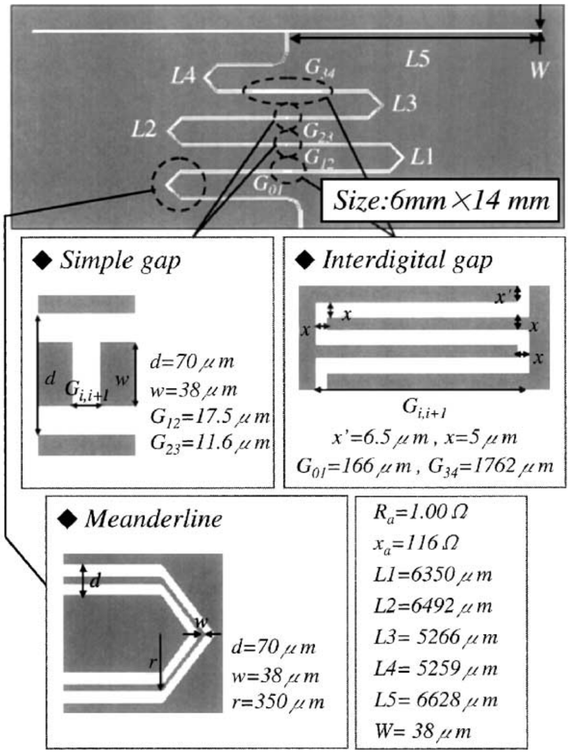

Fig. 2. Geometry of the slot antenna fed by meander CPW transmission line filter with $n = 3$.

where $x_a = (\omega_0/2)(\partial X_a/\partial\omega)|_{\omega=\omega_0}$ is the reactance slope parameter at the series resonance of the antenna impedance.

In Fig. 2, we show an example of a slot antenna which is fed by the meander CPW transmission line. Using the measured input impedance of the slot antenna we designed the practical matching circuit based on the Chebyshev filter with $n = 3$. We were able to design an impedance matching circuit which matches the small antenna resistance of $R_a = 1\ \Omega$ and the reactance slope parameter of $x_a = 116\ \Omega$, corresponding to the ratio of the impedance matching $Z_0/R_a = 50$ for $Z_0 = 50\ \Omega$. The length of the half-wavelength resonator and the geometry of the inverters are decided in the same manner as described in [6]. By adopting the meanderline geometry for the CPW transmission line, we were able to integrate the whole circuit onto 6 mm × 14 mm substrate.

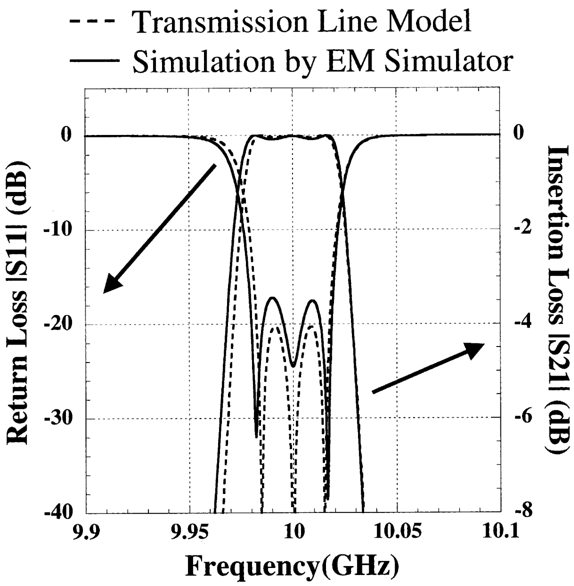

Fig. 3. Simulation results for the return loss $|S_{11}|$ dB and the insertion loss $|S_{21}|$ dB of the antenna with $R_a = 1\ \Omega$.

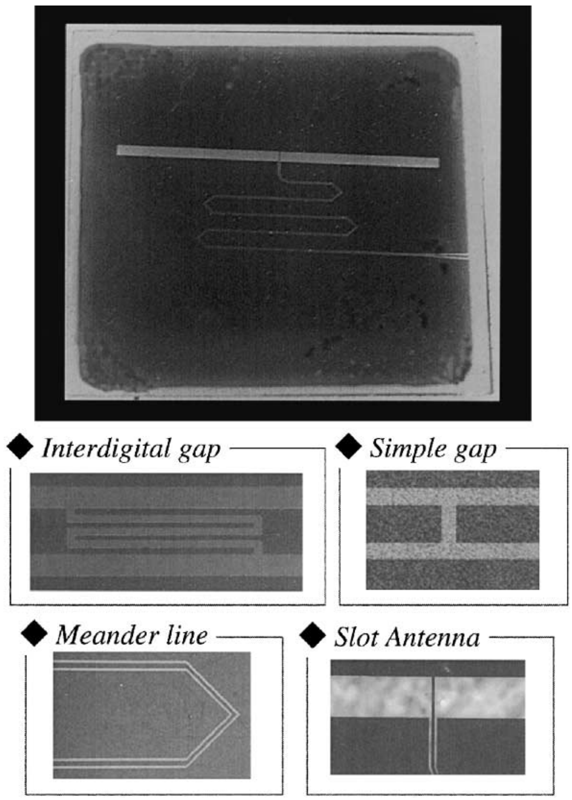

Fig. 4. Experimental geometry of the device.

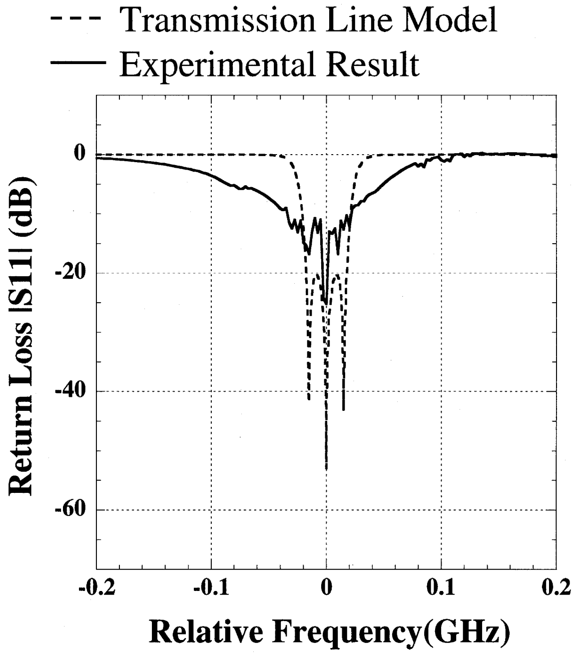

Fig. 5. Observed frequency characteristics of the device.

In Fig. 3, we show the frequency characteristics of the return loss $|S_{11}|$ dB obtained by the EM simulator. The designed values are $\omega_0/2\pi = 10$ GHz, $w = 0.35\%$ and $RL = 20$ dB. The insertion loss $|S_{21}|$ dB calculated from the relation $|S_{21}|^2 = 1 - |S_{11}|^2$ also shown. Broadband impedance matching is able to be achieved.

3. Experimental

In order to confirm the proposed design theory we carried out the experiment. In Fig. 4 we show the pattern of the slot antenna with the meander-line three-pole filter fabricated by a YBCO thin film on a MgO substrate with the dimension of 15 mm × 15 mm. In Fig. 5 we show the observed return loss of the device, where we obtained the return loss as large as 10 dB. The obtained result is in a reasonable agreement with that expected from the design theory. From these results we see that the validity of the proposed design theory for the antenna combined with a bandpass filter is confirmed by the experiment.

4. Conclusion

A superconducting slot antenna combined with a bandpass filter composed of CPW meanderline resonators has been designed and tested. Designed frequency characteristics of the return loss are confirmed by the simulation with EM simulator and the experiment. Using the present theory we might integrate small antenna directly coupled to the filter, leading to a miniaturized microwave receiver made of fully superconducting components.

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