Measurements of phase shifts in YBCO transmission lines for evaluation of kinetic inductance change

R Ishida1, T Goto1, H Shimakage1, M Takeda2

1 Graduate School of Science and Engineering, Ibaraki University, Hitachi, Ibaraki 316-8511, Japan
2 Graduate School of Integrated Science and Technology, Shizuoka University, Hamamatsu, Shizuoka 432-8011, Japan

e-mail : 18nm610a@vc.ibaraki.ac.jp

Abstract. We fabricated a coplanar waveguide (CPW) using high temperature superconductor YBa2Cu3O7−δ (YBCO) and evaluated its characteristics for the realization of a superconducting parametric amplifier. A YBCO thin film with a film thickness of 200 nm was formed by the PLD method using a YAG laser on a 10 × 10 mm MgO substrate. The YBCO thin films were processed into the CPW shape with a line width of 8 μm, a gap width of 8 μm and a line length of 5 mm by photolithography and sputter etching. Using a network analyzer, phase differences of microwave were measured at dc current bias from 0 mA to 14 mA. From the measurement results, it was found that the phase difference decreased with increasing temperature. In addition, it was found that the phase shifts greatly varied near the superconducting transition temperature at each current bias. We observed a maximum phase difference Δθ of -0.08 rad at a bias current of 14.0 mA, which is the closest to the transition temperature. A parametric gain was estimated to be 0.15 dB from the measured maximum phase difference.

1. Introduction

As the terahertz wave lies between the radio waves and light waves, the developments of the terahertz devices are still undeveloped. However, in the terahertz band, there are many unique spectra of many materials, which is called a fingerprint spectrum. From its characteristics, applications in various fields such as life science and security are expected [1]. At present, the use of terahertz waves has technical difficulties such as improvement of S/N ratio, and devices such as detectors and amplifiers are under development. Regarding the amplifier, HEMT (High Electron Mobility Transistor) amplifiers [2] has been utilized in the microwave band for many years. HEMTs are the typical device as the microwave amplifier with wide band characteristic. Furthermore, they have already been put into practical use for satellite broadcasting equipment, and so on. However, its noise performance remains at several tens of times of the quantum limit. On the other hand, the operation of the superconducting parametric amplifier, which utilizes a transmission line, has been proposed recently [3-7]. In general, the superconducting transmission line has two inductances such as the kinetic inductance ($L_k$) and a magnetic inductance ($L_m$), and then a total inductance ($L_T$) is the sum of the two values. The $L_k$, which is an intrinsic inductance of the superconductor transmission line, plays a main role for the operation of the parametric amplifier. Therefore, in the superconducting parametric amplifier, the value of $L_k$ has to be dominant over $L_m$. In general, the $L_k$ has a nonlinearity with respect to applied current $I$ as follows:
\[ L_k(I) \approx L_k(0) \left[ 1 + \left( \frac{I}{I^*} \right)^2 \right], \]  

where \( I^* \) is the strength of the nonlinearity [3]. In superconducting parametric amplifiers using Nb as a superconductor, it is reported that amplification of 10 dB can be obtained at 9 to 11 GHz [3]. The results showed the wideband operation, high dynamic range, and low noise performance in the microwave band. However, since the upper limit response frequency of Nb is around 700 GHz, it does not operate in the terahertz band. Therefore, in order to realize an amplifier operation in the terahertz band, we have been studying a superconducting parametric amplifier using YBa\(_2\)Cu\(_3\)O\(_7\) (YBCO) with an upper limit response frequency of around 7 THz [8]. The superconducting parametric amplifiers generally are composed of a transmission line, and are required a long and narrow signal line to increase the gain [9, 10]. In this paper, we report on the experimental procedures of the fabrication of the YBCO CPW transmission line and experimental evaluations as the parametric amplifier.

2. Fabrication of YBCO transmission lines and measurement method.

2.1. Fabrication of YBCO transmission lines
First, YBCO thin films are deposited on the MgO substrates by a pulsed laser deposition (PLD) method. After that, annealing treatment is performed in oxygen atmosphere. In the deposition process, the substrate temperature is fixed at 820 °C with an oxygen pressure of 400 mTorr. A YAG laser power density is 60 mJ/cm\(^2\) with a repetition frequency of 10 Hz, and the distance between the target and the substrate is 3.5 cm. The annealing treatment after the deposition is carried out for 60 minutes at an oxygen pressure of 300 Torr and a temperature of 430 °C. After that, a coplanar line with a line width of 8 \( \mu \)m, a gap width of 8 \( \mu \)m, and a line length of 5 mm is formed by photolithography and sputter-etching. The sputter-etching is performed for 70 minutes at an argon pressure of 4.0 mTorr and a supply power of 40 W. Figure 1 shows a picture of the fabricated sample. Figure 2 shows a tapered structure for preventing impedance mismatching between the coaxial cable and the coplanar line.

**Figure 1.** Microphotograph of YBCO-CPW

**Figure 2.** Microphotograph of tapered structure
2.2. Measurement method

As shown in equation (1), the $L_k$ of the superconducting transmission line changes nonlinearly when the dc current is applied. A propagation constant consisting of inductance and capacitance also changes as follows:

$$\Delta \theta = |\beta(0) - \beta(I)| = \omega \sqrt{L_T(0)C - L_T(I)C} \cdot l.$$

Here, $\Delta \theta$ is an amount of a nonlinear phase difference and $\beta$ is a propagation constant. We expected that it is possible to evaluate the changes in kinetic inductance by measuring the phase difference. Figure 3 shows a schematic configuration of the phase difference measurement. In the measurement system, the fabricated YBCO coplanar transmission line was connected to the SMA connector and cooled to a low temperature by a refrigerator. The microwave was introduced into the YBCO-CPW using a network analyzer, and dc current was supplied using a bias Tee.

![Figure 3. Measurement setup](image)

3. Measurement results of phase difference on the YBCO transmission line

Using the measurement system (Fig. 3), the transmission characteristics and the phase difference of the fabricated sample were measured. In order to investigate the superconducting critical temperature of the CPW signal line, resistance-temperature (R-T) characteristics at each bias current were measured. The measurement results are shown in Figure 4. Although the measurements were made by a two-terminal measurement, the value of contact resistance was subtracted in the Figure 4. The measurement was implemented by changing the applied current from 1.0 mA to 14.0 mA. As the current value increased, a decrease of the zero-resistance temperature was observed, which reflects the critical current of the thin film. Next, the phase difference during current bias were measured with the network analyzer. The measurements were carried out at around 4 GHz and power of -10 dBm. Figure 5(a) shows temperature dependences of the phase difference when the applied current was varied from 0.0 mA to 14.0 mA. From figure 5(a), the phase difference tends to decrease as the temperature increases for all bias currents. The measurement result caused by the modulation of the kinetic inductance due to temperature change. Moreover, the phase difference greatly changes around the superconducting transition temperature for all bias currents. Figure 5(b) shows an enlarged view from 20 K to 30 K in Figure 5(a). When the temperature was about 25 K, a large phase difference with the current bias of 14.0 mA was observed.
Next, the bias current dependence of the phase difference amount $\Delta \theta$ at 25 K is shown in Figure 6. Here, the plots were normalized with the phase difference $\Delta \theta$ of 0 rad at bias current of 0 mA. We observed the phase difference $\Delta \theta$ of -0.08 rad at 14.0 mA, which was at the closest to the transition temperature. A solid line in the figure 6 is the phase difference $\Delta \theta$ numerically calculated from the shape of YBCO-CPW using a theoretical equation [11]. The experimental results were very close to the numerical calculations. Therefore, this phase difference $\Delta \theta$ is thought to be due to the kinetic inductance modulation by the current bias. Similar measurements are made at different temperatures, and amplification gains were calculated from equation (3);

$$G_\theta = 1 + (\Delta \theta)^2.$$  

At 51 K, the maximum phase difference was observed. Figure 7 shows the parametric amplification gains calculated from the equation (3) with the measured phase difference. Although the highest gain was calculated of 0.15 dB as shown in Figure 7, the value was obtained just below the superconducting transition temperature. It implies that a dynamic range of the signal is thought to be very small for assuming the practical operation. Improvement of coplanar waveguide structure is essential, and the fabrication of CPW with narrower line-width and longer line-length has been being under study. Also,
since the amplification gain is proportional to the length of the transmission line from the expression (2), signal gain would be the higher with the longer transmission line.

![Figure 6. Bias current dependence of phase difference Δθ at 25 K. The closed circles are measured values. The solid line is numerical calculation.](image)

![Figure 7. Parametric amplification gain calculated from phase shift Δθ at 51 K.](image)

4. Conclusion
In this research, in order to realize the YBCO superconducting parametric amplifiers which have the potential of the terahertz band operation, the results of phase difference measurements of the YBCO CPWs were reported. The CPW with the line width of 8 μm and the line length of 5 mm was successfully fabricated, and the phase difference were observed under applying the DC bias currents. Although the phase differences were small at low temperature, the large phase differences were obtained near the critical temperature at each bias current. The results are roughly in agreement with that of numerical calculation by the theoretical kinetic inductance behavior. From the results, it implies that the phase difference obtained by the measurements are attribute to the modulation of the kinetic inductance. Moreover, using the measurement results of the phase difference at 51 K, the expected parametric gain was estimated to be 0.15 dB under bias current of 6.0 mA. However, it was impossible to obtain large phase difference especially for small bias currents. To get the large kinetic inductance modulation, the line width and the length of the CPW should be smaller and longer, respectively. In order to realize the YBCO parametric amplifier, although the required practical gain depends on each application, we are proceeding the CPW configuration improvement. Moreover, as it is important to realize a phase matching for the parametric amplifier operation, we are designing the modulation structure of the CPW.

References
[1] Federici J F, Schulkin B, Huang F, Gary D, Barat R, Oliveira F and Zimdars D 2005 *Semiconductor Science and Technology*. 20 S266
[2] Akgiray A H, Weinreb S, Leblanc R, Renvoise M, Frijlink P, Lai R and Sarkozy S 2013 *IEEE Trans. Microw.* 61 3285-97
[3] Eom B Ho, Day P K, LeDuc H G and Zmuidzinas J 2012 *Nature Phys.* 8 623-7
[4] Bockstiegel C, Gao J, Vissers M R, Sandberg M, Chaudhuri S, Sander A, Value L R, Irwin K D and Pappas D P 2013 *Journal of Low Temperature Physics*. 176 476-82
[5] Chaudhuri S, Gao J and Irwin K 2015 *IEEE Transactions on Applied Superconductivity*. 25 1500705
[6] Vissers M R, Erickson R P, Ku H S, Vale L R, Wu X, Hilton G C and Pappas D P 2016 *Applied Physics Letters*. 108 012601
[7] Adamyan A A, de Graaf S E, Kubatkin S E and Danilov A V 2016 *Journal of Applied Physics.* 119 no. 8

[8] Goto T, Takeda M and Shimakage H 2017 The 78th JSAP Autumn Meeting, 6a-PB1-45

[9] Takeda M 2015 *IEICE Technical Report* **114** no. 406, SCE2014-50, pp. 7-12

[10] Hansryd J, Andrekson P A, Westlund M, Li J and Hedekvist P O 2002 *IEEE J. Selected Topics in Quantum Electron.* **8** 506-20