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Third-harmonic generation from Y–Ba–Cu–O bicrystal Josephson junctions in coplanar waveguides

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Abstract. We report harmonic generation from a bicrystal Josephson junction fabricated in the middle of a 50 Ω coplanar waveguide (CPW). Microwave radiation was injected at one end of the CPW transmission line, and the fundamental and third-harmonic powers were measured. A decrease of the fundamental transmitted power related to thermal breakdown was observed. The third-harmonic output power from the junctions was a complicated function of the input power, showing many non-third order-effects.

1. Introduction

In this paper, we report results on microwave harmonic generation from Y–Ba–Cu–O bicrystal junctions. Such measurements are useful in comparing models for nonlinear behaviour in high-T_C RF devices.

High-T_C passive devices such as microwave filters are candidates for commercial applications [1]. The advantage of a high-T_C filter is the very high Q value compared with normal metal designs, which results from low loss in the superconductor [2]. There are difficulties modelling and designing devices using high-T_C thin films. For example, high-T_C materials exhibit nonlinear effects, producing undesirable high-order harmonics and intermodulation products in filters. Therefore studies about nonlinearity are essential for applications.

In the weakly coupled grain model for superconducting thin films [3], the film is described as a network of grain boundaries, each of which acts as a Josephson junction. Yoshida *et al* showed the residual surface resistance to be in agreement with this model experimentally [4]. Habib *et al* demonstrated the nonlinearity of a Josephson junction by placing it in the centre of a stripline resonator [5]. Our group has evaluated nonlinearity by third-order intercept techniques [6] and developed a model using nonlinear inductance [7] in high-T_C thin films.

For the experiments described here, a YBCO bicrystal junction is fabricated in the centre of a coplanar waveguide (CPW). The input signal is applied at one end, and the first- and third-harmonic outputs are measured at the opposite end using a cryogenic microwave probe station. The fundamental signal transmission behaviour and third-harmonic generation characteristics will be discussed.

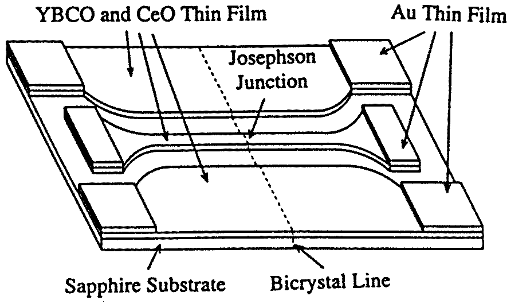

Figure 1. Schematic drawing of the sample with the bicrystal Josephson junction fabricated in the centre of coplanar waveguide.

2. Experiments

2.1. Junction fabrication

A schematic drawing of the device is shown in figure 1. The thin films were grown by pulsed-laser deposition on sapphire bicrystal substrates with buffer layers. The 20 nm CeO_2 buffer layers were grown at a substrate temperature of 800 °C, an oxygen pressure of 53 Pa (400 mTorr) and a repetition rate of 1 Hz. The 140 nm Y–Ba–Cu–O thin films were grown at a substrate temperature of 770 °C, an oxygen pressure of 103 Pa (770 mTorr) and a repetition rate of 10 Hz. The typical critical temperature of the unpatterned film was 89 K. The films were patterned into CPWs using standard photolithography and ion beam etching. The bicrystal line was aligned to the centre of the CPW. To reduce contact resistance between the Y–Ba–Cu–O and the probe tips, 150 nm Au contact pads were fabricated by a lift-off process. The centre line widths of the CPWs are 92 μm, 64 μm, 32 μm and 16 μm. They are designed to have 50 Ω characteristic impedance to match the external circuit impedance. The length of the line is fixed at 1 mm.

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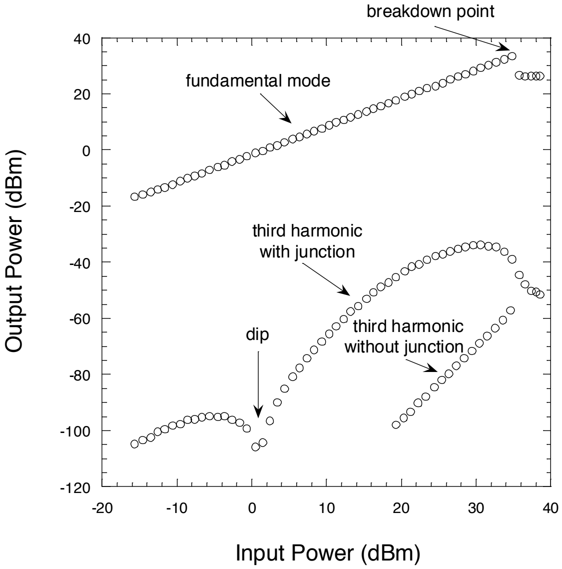

Figure 2. Fundamental signal output and third harmonics as a function of input power. The line width is 32 μm and substrate temperature is 60 K.

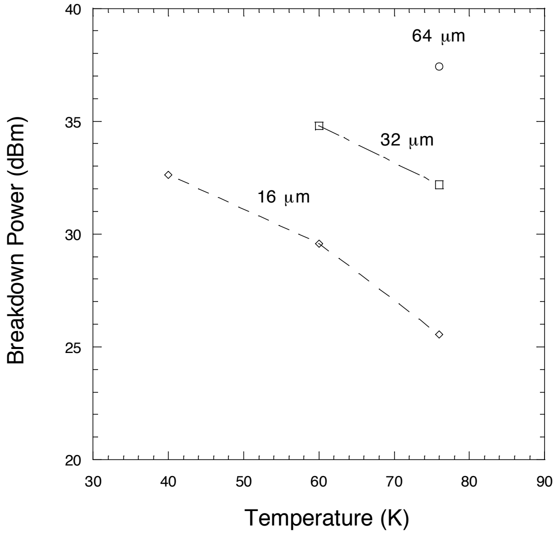

Figure 3. Temperature dependence of the breakdown power. The higher substrate temperature results in lower breakdown power, and the wider lines have a higher breakdown power.

2.2. Microwave measurement

The measurement system is described in detail in [7]. The sample is mounted on a cold head, which is cooled using liquid helium. The temperature is well controlled using a PID controller, ranging from 40 K to 85 K. A continuous signal from a network analyser is amplified approximately 40 dB and then goes through a 20 dB directional coupler for input power measurement. After passing through a 3 GHz low-pass filter, the signal is introduced to the CPW using high-bandwidth coplanar probes. The output signal from the Josephson junction is extracted from the other end of the CPW. The harmonic signals are sampled using a second 20 dB directional coupler. The signals go through a 6 GHz high-pass filter and are measured using a spectrum analyser. Before measurement of the bicrystal sample, we measured the third harmonics from a CPW without a Josephson junction, fabricated on the same chip. This third-harmonic power was more than 10 dB lower than that of a CPW with a junction. Therefore, most of the third-harmonic output on the samples we now discuss is thought to be from the bicrystal Josephson junction and not from the CPW line.

3. Results and discussion

3.1. Fundamental signal output

Figure 2 shows the fundamental signal and third-harmonic outputs of the 32 μm wide junction at 60 K. The third-harmonic output using the CPW line without Josephson junction is also plotted. We fit the fundamental output with a line of slope unity. For the same-size CPW line without Josephson junction, this fitting was the same within the measurement uncertainty, implying that the insertion loss due to the Josephson junction is very low. However, a sudden breakdown can be seen at 32 dBm in figure 2. This behaviour also appeared at other temperatures and in the waveguides with different widths but did not appear in the waveguides without junctions. The breakdown power is shown in figure 3 as a function of temperature and junction width. The higher substrate temperature results in lower breakdown power, and the wider lines have a higher breakdown point power. Because of the output power limit from the power amplifier, the results both for the 92 μm CPW and for the other lines at low temperature do not show the breakdown power. Using the formula $P = I^2 Z_0/2$, we roughly estimated the high-frequency current using the characteristic impedance of $Z_0 = 50\ \Omega$. For the 16 μm width at 60 K, the average breakdown current was estimated to be 84 mA. This value is many times larger than we expect for the critical current of a 16 μm junction on a 24° bicrystal [8]. We attribute this phenomenon to the critical current of the CPW line being exceeded, the critical current perhaps being reduced by heating due to small local dissipation at the junction.

3.2. Third-harmonic power

A dip of the third-harmonic power can be seen near 0 dBm in figure 2. Figure 4 shows the third-harmonic power for the 64 μm line width CPW at 40, 60 and 76 K. The dip points were 5.5 dBm at 40 K and 2.6 dBm at 60 K. The dip cannot be seen at 76 K owing to the spectrum analyser noise limit. This behaviour was observed in junctions with other widths. We confirmed that the location of the power dip increases with increasing line width. We also estimated the high-frequency current to be 11.9 mA at 40 K and 8.5 mA at 60 K. These values are close to the estimated critical current of a 64 μm wide Josephson junction [8]. The power at the dip as a function of substrate temperature is illustrated in figure 5. The power at the dip of wider CPW is higher than that of smaller ones, suggesting that this is related to the junction's critical current.

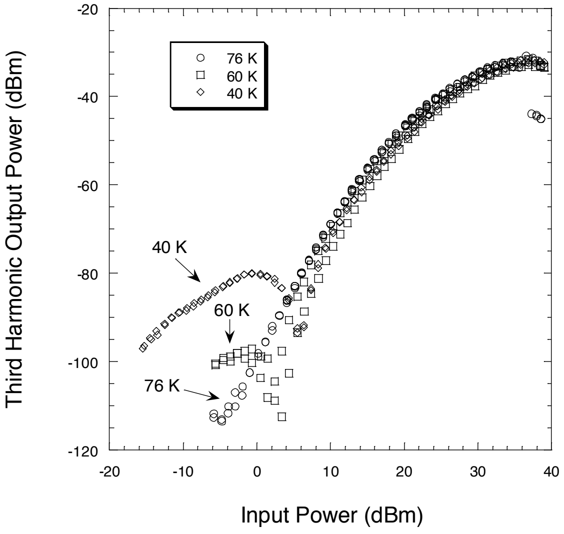

Figure 4. Third-harmonic power as a function of input power. The line width of the coplanar waveguide is 64 μm, and the substrate temperatures are 40, 60 and 70 K. The dips were observed at input powers of 5.5 dBm at 40 K and 2.6 dBm and 60 K.

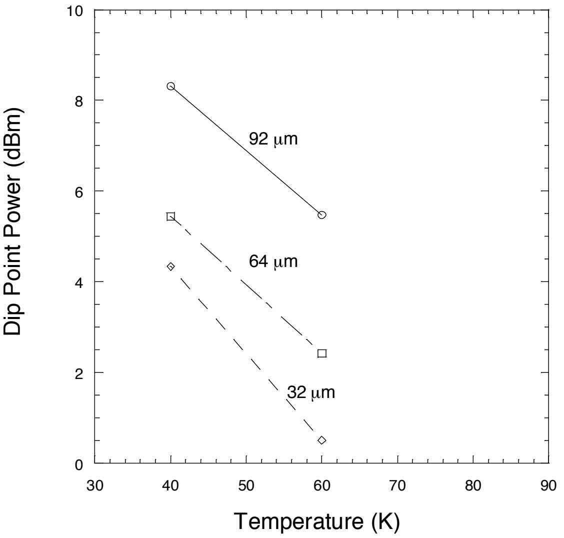

Figure 5. Dip point power as a function of substrate temperature. The dip point power of wider coplanar waveguides is bigger than that of smaller ones.

The behaviour above the dip has little temperature dependence and the slope is decreasing with increasing input power, as seen in figure 4. In the CPW without a junction, the third-harmonic power has a slope of 3 when plotted logarithmically versus input power, and the higher substrate temperature results in lower third-harmonic power [9]. Furthermore, the temperature dependence at powers below the dip is opposite of that of a plain thin film in the measured power range. To understand this further we are working with both shunted-junction models and the nonlinear Josephson kinetic inductance.

4. Conclusion

We reported the behaviour of fundamental signal transmission and third-harmonic generation in YBCO coplanar waveguides with imbedded bicrystal Josephson junctions. The fundamental signal transmits through the Josephson junction with low attenuation. However, breakdown of the transmission appeared at high input signal power. We estimated the high-frequency current and concluded that the breakdown was related to the critical current density of the film itself. In the measurement of the third harmonic, a dip in the output power was observed. The temperature dependence of the third harmonic is quite unlike that of CPW lines without junctions. The details of this behaviour will be analysed by further studies of the temperature and linewidth dependence and by numerical modelling.

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