Available online at www.sciencedirect.com
SciVerse ScienceDirect
Physics Procedia 36 (2012) 199 – 204
Physics Procedia

Superconductivity Centennial Conference

Generation and detection of THz radiation using intrinsic Josephson junctions

Akinobu Irie*, Dai Oikawa, Gin-ichiro Oya

Department of Electrical and Electronic Systems Engineering, Utsunomiya University, 7-1-2 Yoto, Utsunomiya 321-8585, Japan

---

Abstract

We present the generation and detection of terahertz radiation using intrinsic Josephson junctions (IJJs) in $Bi_2Sr_2CaCu_2O_y$ single crystals. This approach allows us to detect THz radiation from large stacks consisting of a few hundred intrinsic Josephson junctions. The lateral dimensions of the fabricated IJJ oscillator mesa range from 290×50 to 290×90 μm^2 and the number of IJJs which constitute the mesas is between 100 and 450, while the small mesa with the lateral dimensions of 5×5 μm^2 is used as the high sensitive THz detector. The largest emission is always observed when the oscillator is biased at the negative resistance region of the current-voltage characteristics. We find that the emission frequency corresponds to the second harmonics of the in-phase cavity resonance mode. This is consistent with the emission condition of the case of thick IJJ stacks reported previously.

Keywords: intrinsic Josephson junctions, terahertz radiation, cavity resonance

---

1. Introduction

The terahertz (THz) frequency range is receiving considerable attention because of its many possible applications such as imaging, nondestructive inspection, and so on [1]. Although a variety of THz technologies have been developed, due to the lack of effective THz wave generation devices in the past, the THz frequencies still are one of the most underdeveloped electromagnetic spectra, so that developing compact and coherent solid-state THz sources remains to be a subject of intensive research efforts.

Since the discovery of the intrinsic Josephson effect in high-T_c cuprate superconductor such as $Bi_2Sr_2Ca Cu_2O_y$ [2, 3], strongly coupled intrinsic Josephson junctions (IJJs), which are atomically stacked Josephson junctions, have been expected to be novel source of intense, coherent THz radiation because of the superconducting energy gap frequency in the THz range. Therefore, until now, there have been many theoretical and experimental works on the electromagnetic wave radiation from IJJs [4, 5, 6, 7, 8]. However, apparent THz radiation from IJJs has not been observed experimentally for the past ten years or more except for few observations of unsynchronized radiation [7].

---

[*] Corresponding author.
Email address: `iriea@cc.utsunomiya-u.ac.jp` (Akinobu Irie)

doi:10.1016/j.phpro.2012.06.071

Recently, coherent THz radiation from large rectangular mesas containing more than 600 IJJs has been successfully observed by Ozyuzer *et al*. [9]. Such a strong emission is considered to be due to an excitation of the cavity resonance mode induced by ac Josephson effect. The subsequent energetic works performed by the same group also support this mechanism [10, 11]. On the other hand, more recently Wang *et al.* have observed other type of THz radiation from IJJs, which comes from the cavity resonance limited by hot spot [12]. Furthermore, the emission mechanism hasn't been established completely because the THz emission has been experimentally observed by only a few groups. Besides, the emission from a stack with < 500 IJJs is hardly studied. For better understanding of the emission mechanism, it may be important to study the emission properties in stacks with a few hundreds IJJs or less .

Here, we report on the first observation of the THz radiation from stacks containing less than 300 IJJs. In this study, we use the small IJJ stack as high sensitivity THz detector.

2. Samples

2.1. IJJ oscillator

In this work, we used as-grown BSCCO single crystals prepared by a conventional melting method[13]. Typical critical temperature of the crystals is about 85 K. IJJ THz oscillators consisting of large mesa structures patterned on BSCCO single crystal surfaces were fabricated by photolithography and Ar ion milling. The dimensions of the oscillator mesas are 290 μm in length L, 50, 70 and 90 μm in width W, and 150 – 450 nm in hight H. The electrical contact to the mesa was provided by a 200 nm thick Au layer. A schematic view and optical image of the fabricated IJJ oscillator are shown in Fig. 1. As seen in this figure, in our samples, the IJJ oscillator is formed on a large base mesa because such a structure can provide an uniform distribution of bias current to the IJJ oscillator.

Current-voltage ($I - V$) characteristics of the IJJ oscillator were measured by means of two terminal method. A typical example of the measured $I - V$ characteristic at 4.2 K is shown in Fig. 2(a). The size of oscillator mesa is $290 \times 70\ \mu\text{m}^2$ and it contains 110 junctions. The $I - V$ curve is characterized by a negative resistance on the quasiparticle branch, which is due to the heating effect and is one of common features in large samples [12]. Furthermore, it is found that most IJJs in the mesa switch simultaneously to resistive state at $I = 33$ mA. Such collective switching means that the critical current of the constituent IJJs in the mesa is nearly equal to each other. However, the critical current density J_c of about 160 A/cm^2, estimated from the critical current $I_c = 33$ mA, is somewhat small compared with that of small mesas. As shown in Fig. 2(b), all oscillator mesas fabricated in this study have smaller J_c values ranging between 100 and 270 A/cm^2 at 4.2 K. This is because the oscillator mesa is much larger than the Josephson penetration depth and hence the current injection is nonuniform.

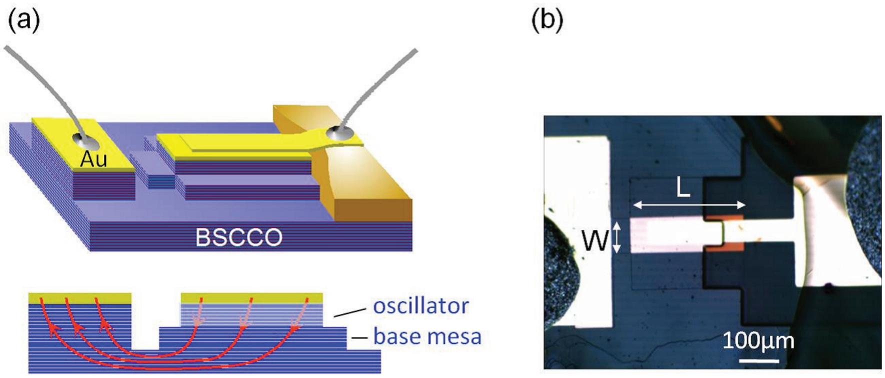

Fig. 1. (a) A schematic view of the sample and cross-section of the mesa. (b) Optical photograph of the fabricated sample.

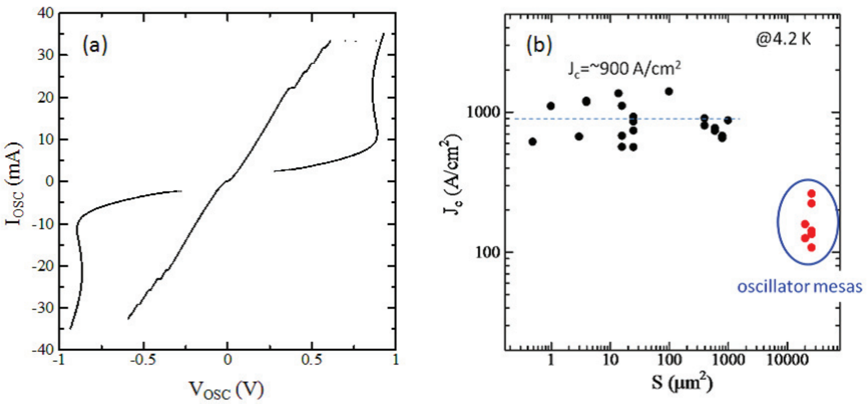

Fig. 2. A typical $I - V$ characteristic of the fabricated oscillator mesa ($N = 110$) at 4.2 K. The lateral dimensions of the mesa is $290 \times 70\ \mu\mathrm{m}^2$. (b)The critical density J_c at 4.2 K as a function of mesa size S. The data of the oscillator mesas are indicated by the red points.

2.2. *IJJ detector*

In order to detect THz radiation from IJJ oscillator, the detector which is sensitive to the THz electromagnetic field is necessary, so that we used small IJJ stacks as the detector. Figure 3(a) shows the optical photograph of the IJJ detector consisting of a $5 \times 5\ \mu\mathrm{m}^2$ mesa with a bow-tie antenna. Fabrication process of the IJJ detector is similar to a small IJJ mesa reported previously [14]. The $I - V$ characteristics of the IJJ detectors also show typical highly hysteretic multiple branches. Then, in two or three terminal measurement it is often observed that the critical current of the first branch is much smaller than that for the rest of branches. This small I_c arises from a weak IJJs formed at the top of mesa, i.e., the so-called *surface IJJ* [15]. An example measured at 4.2 K is shown in Figs. 3(b) and 3(c). It is found that the I_c of the inner IJJs is $\sim 170\ \mu$A, while that of the surface IJJ is only 10 μA. The surface IJJ is very sensitive to an electromagnetic field because of small I_c and hence it was used for detection of THz radiation from the IJJ oscillator.

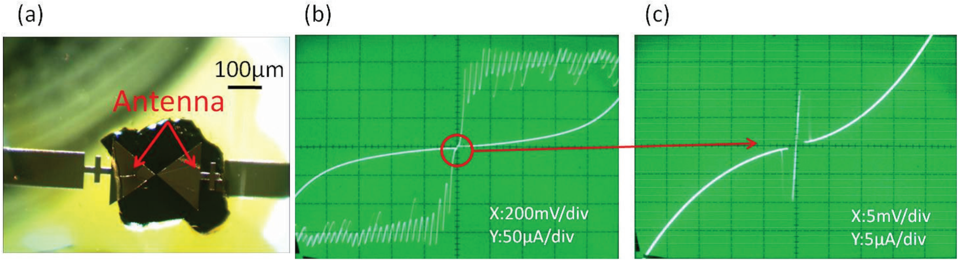

Fig. 3. (a) Optical photograph of the IJJ detector with an antenna structure. (b) $I - V$ characteristic of the IJJ detector mesa at 4.2 K. The lateral dimensions of the mesa is $5 \times 5\ \mu\mathrm{m}^2$ and the number of IJJs in the mesa is 37. (c) $I - V$ characteristic of the surface IJJ in the detector mesa.

3. Experimental setup

Experiments were performed at 4.2 K. A block-scheme of our experimental setup for detection is shown in Fig. 4(a). The IJJ detector chip was placed about 1 cm away from the IJJ oscillator chip and they were driven by individual bias circuit. During experiments, the bias current of the oscillator I_{OSC} was swept slowly ($\sim$ 1 mHz) and the dc current I_B was applied to the detector. The current - voltage ($I_{OSC} - V_{OSC}$) characteristic of the oscillator mesa and the voltage V_{DET} of the detector mesa were recorded by an personal computer connected to digital multimeters (DMM). In this system, the electromagnetic wave radiated from the oscillator mesa can be detected by the modulation of V_{DET} because the critical current of the surface IJJ in the detector mesa is suppressed depending on the power of the receiving electromagnetic wave as shown in Fig. 4(b).

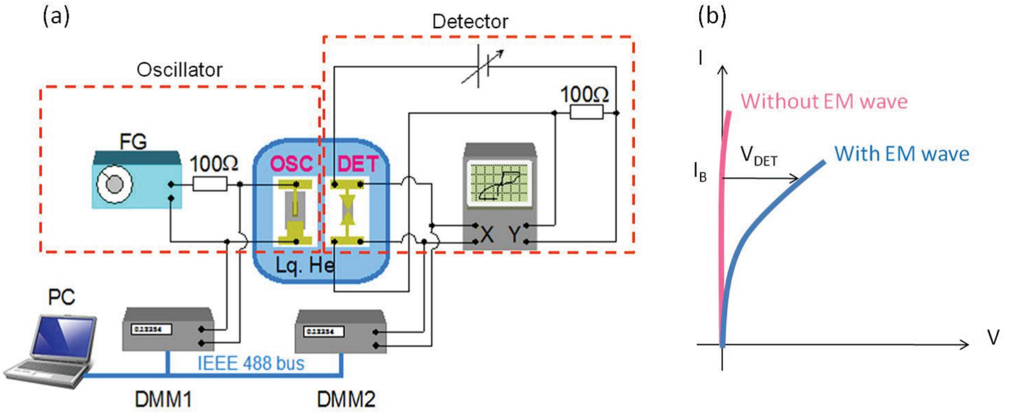

Fig. 4. (a) Experimental setup for detection of THz radiation from the IJJ oscillator. (b) Principle of THz detection using the surface IJJ.

4. Results and discussion

Figure 5(a) shows the $I_{OSC} - V_{OSC}$ characteristic of the $W = 50$ μm oscillator mesa at 4.2 K together with the detector voltage V_{DET}. The number N of IJJs in the mesa is estimated to be about 200 from its height. One can see that V_{DET} shows clear peaks around ±1 V. Note that these peaks are always observed in a negative resistance region which becomes more apparent if the voltage drop due to a contact resistance is taken into account. This is consistent with recent observations using a Si bolometer. Furthermore, we can except a possibility of the effect of the Joule heating from the oscillator because at even high bias region (> 1.1 V) V_{DET} keeps lower values although the mesa may be considerably heated by a large injection current. Therefore, it seems reasonable to suppose that these peaks of V_{DET} result from the detection of an electromagnetic wave emission from the oscillator mesa.

It is interesting to measure the frequency spectrum of the emitted radiation from the oscillator mesa for understanding of the emission properties of IJJs. However, although our IJJ detector works as a power meter, it can not provide the frequency spectrum analysis. Accordingly we estimate the emission frequency using the Josephson frequency-voltage relation. Figure 5(b) shows the high bias region of the $I_{OSC} - V_{OSC}$ and $V_{DET} - V_{OSC}$ curves shown in Fig. 5(a). The large response occurs at the voltages between 1.0 and 1.1 V. Interestingly, the maximum V_{DET} is obtained at a chaotic region of the $I_{OSC} - V_{OSC}$ curve. By subtracting the voltage drop of the contact resistance from the voltage of 1.02 V at which the maximum response was observed, the net bias voltage V_{OSC} of the oscillator mesa for the largest emission is calculated to be 360 mV. The corresponding emission frequency of $f_{OSC} = 0.87$ THz is estimated by using the relation, $f_{OSC} = V_{OSC}/N\Phi_0$, where Φ_0 is the flux quantum. Furthermore, the emission was confirmed to be stable for a long time and to be reproducible.

In previous studies for thick IJJ stacks of $N \gg 500$, it has been pointed out that the THz emission occurs when the in-phase cavity resonant mode is excited by the Josephson oscillation, i.e., the Josephson frequency matches the in-phase cavity resonance [9]. On the other hand, in our case the oscillator mesa consists of less than 300 IJJs and it is not confirmed whether the emission condition is the same as the case of thick stack.

As well known, N stacked Josephson junctions have N mode velocities and they are given as [16]

$$c_n = c_0 \left[1 - 2S \cos \frac{n\pi}{N+1}\right]^{-1/2} \qquad (n = 1, 2, ..., N), \tag{1}$$

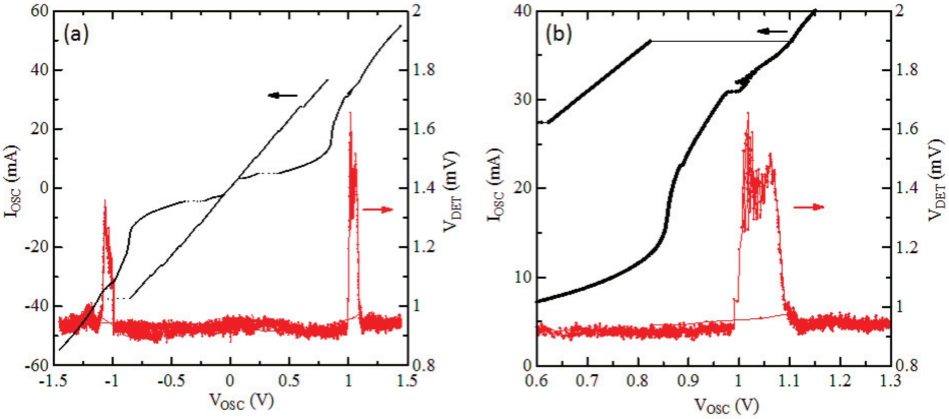

Fig. 5. (a)Current-voltage characteristic of the oscillator mesa with the lateral dimensions of 290 × 50 μm^2 and the voltage of IJJ detector at 4.2 K. The number of IJJs in the oscillator is 200. (b)Enlarged high bias region of Fig. 5(b).

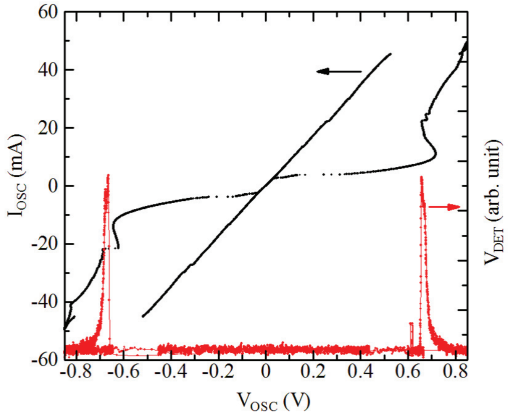

Fig. 6. Current-voltage characteristic of the oscillator mesa and the IJJ detector voltage as a function of the bias voltage of the oscillator at 4.2 K. The lateral dimensions of the oscillator is 290 × 70 μm^2 and the number of IJJs in the oscillator is 290.

where c_0 is the Swihart velocity, $S = -\lambda_L/d' \sinh(t/\lambda_L)$, λ_L is the London penetration depth, t is the superconducting electrode thickness, $d' = d + 2\lambda_L \coth(t/\lambda_L)$, and d is the barrier thickness is the effective barrier thickness. In Eq. (1) c_1 and c_N correspond to the in-phase and out-of-phase mode velocities, respectively. For IJJ stacks of $N \ll 400$, c_1 and c_N in Eq. (1) can be approximated as [17]

$$c_1 \simeq c\sqrt{\frac{d(t+d)}{\varepsilon_r \lambda_{ab}^2}}\frac{N+1}{\pi} \quad \text{and} \quad c_N \simeq \frac{c}{2}\sqrt{\frac{d(t+d)}{\varepsilon_r \lambda_{ab}^2}} \quad (\text{for } 1 \ll N \ll 400). \tag{2}$$

Here, $c = 3 \times 10^8$ m/s is the light velocity in vacuum and ε_r is the relative dielectric permittivity. Using typical values of $\varepsilon_r = 10$, $\lambda_{ab} = 200$ nm, $t = 0.3$ nm and $d = 1.5$ nm for a BSCCO IJJ, we obtain $c_1(N = 200) \simeq 4.1 \times 10^7$ m/s and $c_N(N = 200) \simeq 3.2 \times 10^5$ m/s. We can also estimate that the fundamental in-phase cavity resonance frequency $f_r = c_1/2W$ is about 0.41 THz for $W = 50$ μm, which is a half of the observed emission frequency. Thus we may say that the emission shown in Fig. 5 corresponds to the second harmonics of the in-phase cavity mode and the stack oscillates coherently. However, although we have observed the THz emission for more than 15 samples with different W, the emission frequencies estimated from the emission peak voltage did not always correspond to the cavity resonance mode.

An example is shown in Fig. 6. The width of this sample is 70 μm and $N = 290$. The $I_{OSC} - V_{OSC}$ and

$V_{DET} - V_{OSC}$ characteristics are similar to Fig. 5. Furthermore, it is found that the largest emission occurs at the negative resistance region. In this case, the net voltage of the mesa, which is taking into account the voltage drop of contact resistance, is 401 mV corresponding to the frequency $f_{OSC} = 0.67$ THz, while the estimated cavity resonance frequency is 0.42 THz. Accordingly, the observed emission frequency does not match the in-phase cavity resonance. If we assume that the emission peak shown in Fig. 6 is also caused by the second harmonic cavity resonance, the number of IJJs participating in coherent oscillation can be deduced as $N' = V_{OSC}/2f_r\Phi_0 \simeq 230$, which is about 80 % of 290 expected from the thickness. This is consistent with the observation reported by Wang *et al.* However, to clarify this point the direct measurement of the emission frequency will be necessary.

5. Conclusions

We have investigated THz emission from large intrinsic Josephson junction stacks containing a few hundred junctions by applying a small stack to a detector. We successfully observed the bias-voltage-dependent emission and found that the emission intensity becomes maximum by biasing the negative resistance region on the $I-V$ curve. Our experimental results clearly show the cavity resonance model is valid even for stacks which consist of a considerably small number of junction than to stacks studied so far.

Acknowledgment

The authors wish to thank Dr. K. Yamaki for useful discussions. This work was supported in part by the Grant-in-Aid for Scientific Research (B) Fund from the Japan Society for the Promotion of Science (JSPS).

References

[1] Tonouch M, Cutting-edge terahertz technology. Nature Photonics 2007:**1**:97–105.

[2] Kleiner R, Steinmeyer F, Kunkel G, Müller P. Intrinsic Josephson effects in $Bi_2Sr_2CaCu_2O_8$ single crystals. Phys Rev Lett 1992;**68**:2394–2397.

[3] Oya G. Aoyama N, Irie A, Kishida S, Tokutaka H. Observation of Josephson Junctionlike Behavior in Single-Crystal (Bi, $Pb)_2Sr_2CaCu_2O_y$. Jpn J Appl Phys 1992:**31**:L829-L831.

[4] Tachiki M. Koyama T. Takahashi S. Electromagnetic phenomena related to a low-frequency plasma in cuprate superconductors. Phys Rev B 1994:**50**:7065-7084.

[5] Kleiner R. Koyama T. Müller P. Intrinsic Josephson effects in high-T_c superconductors. Phys Rev B 1994:**49**:1327–1341.

[6] Leer K. Wang T. Iguchi I. and Tachiki M. Hirata K. Mochiku, T. Josephson plasma emission from $Bi_2Sr_2CaCu_2O_y$ intrinsic junctions due to quasiparticle injection. Phys Rev B 2000:**61**:3616-3619.

[7] Batov I. E Jin X. Y. Shitov S. V. Koval P. Mu”ller P. Detection of 0.5 THz radiation from intrinsic $Bi_2Sr_2CaCu_2O_2$ Josephson junctions. A@@l Phys Lett 2006:**88**:262504.

[8] Bae M. -H. Lee H. -J. Choi J. -H. Josephson-vortex-frow terahertz emission in leyered high-T_c superconducting single crystals. Phys Rev B 2007:**98**:027002.

[9] Ozyuzer L. Koshelev A. E. Kurter C. Gopalsami N. Li Q. Tachiki M. Kadowaki K. Yamamoto T. Minami H. Yamaguchi H. Tachiki T. Gray K. E. Kwok W. -K. Welp U. Emission of Coherent THz Radiation from Superconductors. Science 2007:**23**:1291-1293.

[10] Kadowaki K. Yamaguchi H. Kawamata K. Yamamoto T. Minami H. Kakeya I. Welp U. Ozyuzer A. Koshelev A. Kutter C. Gray K. E. Kwok W. -K. Direct observation of terahertz electromagnetic waves emitted from intrinsic Josephson junctions in single crystalline $Bi_2Sr_2CaCu_2O_{8-\delta}$. Physica C 2008:**468**:634-639.

[11] Minami H. N. Orita N. Koike T. Ymamoto T. Kadowaki K. Continuous and reversible operation of Bi2212 based THz emitters just below T_c. Physica C 2010:**470**:S822-S2010.

[12] Wang H. B. Gué non S. Gross B. Yuan J. Jiang Z. G. Zhong Y. Grünzweig M. Ishii A. Wu P. H. Hatano T. Koelle D. Kleiner R. Coherent terahertz emission of intrinsic Josephson junction stacks in the hot spot regime. Phys Rev Lett 2010:**105**:057002.

[13] Irie A. Sakakibara M. Oya G. Grouth and tunneling properties of $(Bi,Pb)_2Sr_2CaCu_2O_y$ single crystals. IEICE Trans. Electoron. 1994:**E77-C**:1191-1198.

[14] Irie A. Heim S. Schromm S. Müßle M. Nachtab T. Gódo M. Kleiner R. Múller P. Oya G. Critical current of small $Bi_2Sr_2CaCu_2O_{8+\delta}$. Phys Rev B 2000:**62**:6681-6686.

[15] Doh Y. -J. Kim J. Kim K. -T. Lee H. -J. Microwave-induced constant voltage steps in surface junctions of $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals. Phys Rev B 2000:**61**:3834-3628.

[16] Sakai S. Ustinov A. V, Kohlstedt G. Petraglia A. Pedercen N. F. Theory and experiment on electromagnetic-wave-propagation velocities in stacked superconducting tunnel structures. Phys Rev B 1994:**50**:12905-12914.

[17] Katterwe S. O. Rydh A. Motzkau H. Kulakov A. B. Krasnov V. M. Superluminal geometrical resonances observed in $Bi_2Sr_2CaCu_2O_{8+x}$ intrinsic Josephson junctions. Phys Rev B 2010:**82**:024517.