LA-UR- 11-02055

Approved for public release;
distribution is unlimited.

Title: Optimized THz emission from intrinsic Josephson junctions

Author(s): N. A. Moody, L. N. Boulaevskii, V. Pavlenko

Intended for: SPIE Defense, Security, and Sensing 2011
Orlando, FL, USA
25 - 29 April, 2011

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the Los Alamos National Security, LLC for the National Nuclear Security Administration of the U.S. Department of Energy under contract DE-AC52-06NA25396. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

TRANSFER OF COPYRIGHT TO SOCIETY OF PHOTO-OPTICAL INSTRUMENTATION ENGINEERS (SPIE)

Title of Paper: Optimized THz emission from intrinsic Josephson junctions

SPIE Paper Number: (xxxx-xx) 8023-18

Author(s): Nathan A. Moody, Lev N. Boulaevskii, Vitaly Pavlenko (LANL)

This signed statement must be returned to SPIE prior to the scheduled publication of the Proceedings or Journal in which the Paper will be published. The intent of this Agreement is to protect the interests of both SPIE and authors/employers and to specify reasonable rights for both parties related to publication and reuse of the material.

The undersigned hereby assign(s) to Society of Photo-Optical Instrumentation Engineers (SPIE) copyright ownership in the above Paper, effective if and when the Paper is accepted for publication by SPIE and to the extent transferable under applicable national law. This assignment gives SPIE the right to register copyright to the Paper in its name as claimant and to publish the Paper in any print or electronic medium.

Authors, or their employers in the case of works made for hire, retain the following rights:

1. All proprietary rights other than copyright, including patent rights.
2. The right to make and distribute copies of the Paper for internal purposes.
3. The right to use the material for lecture or classroom purposes.
4. The right to prepare derivative publications based on the Paper, including books or book chapters, journal papers, and magazine articles, provided that publication of a derivative work occurs subsequent to the official date of publication by SPIE.
5. The right to post an author-prepared version or an official version (preferred version) of the published paper on an internal or external server controlled exclusively by the author/employer, provided that (a) such posting is noncommercial in nature and the paper is made available to users without charge; (b) a copyright notice and full citation appear with the paper, and (c) a link to SPIE's official online version of the abstract is provided using the DOI (Document Object Identifier) link.

Citation format:

Author(s), "Paper Title," Publication Title, Editors, Volume (Issue) Number, Article (or Page) Number, (Year).

Copyright notice format:

Copyright XXXX (year) Society of Photo-Optical Instrumentation Engineers. One print or electronic copy may be made for personal use only. Systematic reproduction and distribution, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper are prohibited.

DOI abstract link format:

<http://dx.doi.org/DOI#> (Note: The DOI can be found on the title page or online abstract page of any SPIE article.)

If the work that forms the basis of this Paper was done under a contract with a governmental agency or other entity that retains certain rights, this Transfer of Copyright is subject to any rights that such governmental agency or other entity may have acquired.

By signing this Agreement, the authors warrant that (1) the Paper is original and has not previously been published elsewhere; (2) this work does not infringe on any copyright or other rights in any other work; (3) all necessary reproduction permissions, licenses, and clearances have been obtained; and (4) the authors own the copyright in the Paper, are authorized to transfer it, and have full power to enter into this Agreement with SPIE.

WHO SHOULD SIGN. This form must be signed by (1) at least one author who is not a U.S. Government employee and (2) the author's employer if the Paper was prepared within the scope of the author's employment or was commissioned by the employer. If not signed by all authors, the author(s) signing this Agreement represents that he/she is signing this Agreement as authorized agent for and on behalf of all the authors.

Nathan A. Moody	4/4/2011
Author's signature	Print name	Date (mm/dd/yyyy)

Bruce Carlson	4/5/11
Authorized Employer signature	Print name	Date (mm/dd/yyyy)
	Title	

U.S. GOVERNMENT EMPLOYMENT CERTIFICATION

A work prepared by a U.S. Government employee as part of his or her official duties is not eligible for U.S. Copyright. If all authors were U.S. Government employees when this Paper was prepared, and the authors prepared this Paper as part of their official duties, at least one author should sign below. If at least one author was not a U.S. Government employee, the work is eligible for copyright and that author should sign the Transfer of Copyright form above.

Author's signature	Print name	Date
--------------------	------------	------

Optimized THz emission from intrinsic Josephson junctions

Nathan A. Moody*, Lev N. Boulaevskii, Vitaly Pavlenko
Los Alamos National Laboratory, Los Alamos, NM, USA 87545

ABSTRACT

Nearly every wavelength from dc to x-rays significantly benefits today's society with a notable exception: the THz or sub-millimeter band. Applications in this range are widespread, penetrating fields ranging from national security to medicine, but remain largely under-utilized due to the difficulty of creating, manipulating, and detecting this type of radiation. Our research focus is THz source development using superconductive Josephson junctions to potentially address the lack of compact, efficient, and tunable source of continuous THz radiation. We review relevant applications for such a source and report an optimized design of a miniature THz emitter using single crystal intrinsic Josephson junctions.

Keywords: THz source, Josephson junction, IJJ, THz emission, BSCCO.

1. INTRODUCTION

In 2004, the NSF and DOE jointly identified THz science as a frontier research area with widespread applications, penetrating entire fields ranging from national security to medicine ^[1-3]. These remain largely unrealized due to the inherent difficulty of directly creating, manipulating, and detecting this type of radiation. Recent experimental ^[4-6] and theoretical studies ^[7-10] have shown that intrinsic Josephson junctions (IJJs), micron-scale structures made of high temperature superconductors, can be made to directly generate and strongly interact with THz signals. As solid-state devices, they offer distinct advantages over other technologies: compactness, high-efficiency, wavelength tunability, narrow-band emission, scalability to high power (as sources), and low power consumption ^[11, 12]. Furthermore, their development could advance the field of THz science by providing additional functions such as THz amplifiers, mixers, (de-)modulators, detectors, and filters ^[4, 13-18].

1.1 Josephson Junction

A Josephson junction is essentially two superconductors separated by a thin insulating layer; a DC voltage applied across the junction causes it to oscillate and emit coherent electromagnetic radiation, with frequency proportional to voltage ($\omega = 2eV_{dc} / \hbar$) up to a limit set by the superconducting energy gap ^[19]. The interaction of a *single* junction with electromagnetic radiation is far too weak to be useful. However, large numbers (~50k) of identical junctions can be made to coherently oscillate resulting in dramatically enhanced emission or interaction, which we show is crucial toward realizing useful devices ^[9, 14]. A primary goal in THz science is a practical THz source, the quest for which has spawned an international R&D effort with widely varying technical approaches ^[20]. The ideal source would be continuous wave (CW), with narrow-band emission that is frequency tunable, and scalable to high power (>1W). The manner in which our source design attempts to address these needs is outlined in detail in later sections of this paper.

1.2 Overview of THz Applications

The so-called "THz gap" refers to the portion of the electromagnetic spectrum from approximately 0.5 to 10 THz in which there are essentially no practical sources of radiation ^[20]. This same spectral region, because of its unique propagation characteristics and interaction with matter (discussed below), corresponds to some of the most exciting applications to date for national security ^[1, 3, 20, 21]. The well established emission techniques for the neighboring microwave and optical regions of the spectrum have proven ineffective for the THz band.

*nmoody@lanl.gov; phone | 505 667-1502; fax | 505 667-8207

The frequency of alternating currents in semiconductors is limited from above by finite electron velocities, while that of conventional lasers is limited from below by non-zero thermal energies which prevent the small electronic transition required for lasing at THz wavelengths. In contrast, the Josephson junction interaction is *particularly suited to operate in the THz band*, as it naturally converts a dc voltage (1 mV corresponds to 0.483 THz) into millimeter wave oscillations via the Josephson effect^[19].

The physics of THz has captured wide interest because it combines the penetrating propagation capability (through fog, dust, select materials) usually associated with microwaves^[20] and diffraction limited imaging resolution and spectroscopy capabilities typically associated with optical systems^[22]. In broadest terms, THz is seen as a bridge between rf and optical technologies. Unlike x-rays, THz is non-ionizing (safe for continuous interrogation of biological tissue) but still retains the ability to penetrate and image tissue or other materials, such as clothes or packaging, to reveal structure and composition. The strongest absorption signatures for bio-agents, explosives, and their precursors are centered in the THz band, corresponding to rotational degrees of freedom and collective molecular motion such as bending and torsional modes^[22]. Together, these absorptions provide the spectral features required to robustly identify many high interest compounds^[20]. For a system of molecules in thermal equilibrium, the coupling strength or peak

absorption coefficient between energy levels m and n is given by: $\alpha_{\max} = \frac{8\pi^2 N F_m \nu_0^2}{3ckT(\Delta\nu)} |\langle m|\mu|n \rangle|^2$, where N is the number of molecules per unit volume, F_m is the number of molecules in the ground state, ν_0 is the transition frequency and $|\langle m|\mu|n \rangle|$ is the dipole matrix element^[23]. Depending upon sample preparation, the linewidth $\Delta\nu$ can be quite narrow (~ 1 MHz) enabling high detection specificity even with small samples ($< 10^{-18}$ moles)^[22]. Explosives detection is among the top potential applications and a number of spectra have been published using single-shot time domain spectroscopy THz systems^[1, 24]. For example, the absorption signature for RDX, a major constituent of C4, is shown in Figure 1, and others have published the spectra of HMX, PETN, TNT, and other materials^[3, 21, 24, 25].

Figure 1. Absorption signatures of C4 precursor materials.

A well known problem among THz-based remote sensing schemes is the effect of atmospheric attenuation and line broadening over appreciable propagation distances^[3]. One solution provides a striking example of how existing technologies can be combined with emerging THz techniques to great effect: for long (~ 1 km) standoff distances, a conventional pulsed CO₂ laser can be used to “pump” or modulate the atmosphere. By introducing a known time delay between the laser pump and THz probe signal and knowing the time scale of the pulse sequence, one can augment the typical 1-D THz specificity matrix (which would be sufficient for up-close absorption spectroscopy) to a 3-D matrix that greatly enhances specificity at long distances^[26].

A recent report^[27] from the Army Research Office on military applications suggests a “THz + X” strategy, where X refers to an existing technology which is coupled to THz in a specific way, based on mission needs: 1.) explosives detection, 2.) chemical detection, and biological detection. For example, existing laser sources may be used to excite a known resonance that can be accurately probed with THz spectroscopy. Or for certain chemicals, pulsed laser

modulation can decompose or vaporize airborne particles into by-products with larger THz cross sections for higher detection sensitivity. In some applications, it may be possible to introduce a reagent or catalyst in the field (i.e., cloud plume) that is known to react with chemical agents, releasing products which themselves have distinct THz spectra^[27]. For molecules with either very broad spectral linewidths or sparse features, dielectric beads can be tuned in size and coated with reagents to have distinct absorptions when a given chemical agent reacts and adheres to the surface. If detectors could be miniaturized and directly deployed in the field, they could be remotely controlled and monitored, greatly enhance sensitivity because the issue of THz atmospheric propagation is minimized. More than a dozen similar scenarios are proposed where mature technologies, when coupled with THz, can be harnessed in versatile ways to solve remote sensing needs. In each case, however, a source and compatible components (ideally miniaturized) would be required to build practical systems.

Very high bandwidth, localized communication networks are also an attractive tactical application of a THz source, due to the beam-like (line of sight) propagation of THz waves and their limited propagation in atmosphere (reducing intercept probability)^[28]. In space applications, line of sight propagation is desired and could enable extremely high data rates for next generation satellite networks.

2. APPROACH

2.1 Conventional Approach to THz

Vacuum electronic devices, such as backward wave oscillators (BWOs), provide milliwatts of tunable power at high efficiency, but are not practical for portable applications due to their large size (and their need for a high-voltage supply and an external magnetic field). Despite their potential for high power, the same is true of all devices based on modulation of a high energy electron beam: their essential component is a large electron beam accelerator which cannot be made portable or lightweight with today's accelerator technologies. Quantum cascade lasers (QCL) have recently emerged as a new THz source, but these require complicated fabrication of quantum wells, lack tunability, and suffer from high power consumption, short lifetime (several hundred hours), and low efficiency. Harmonic THz generation using microwave sources is a commercially available technology, but again limited tunability and low efficiency remains a problem because of the losses associated with harmonic up-conversion. Finally, parametric generation is a common optical-based method of launching THz signals: two laser beams with slightly different wavelengths beat together in a nonlinear medium such as MgO:LiNbO₃. The beat wave can be outcoupled using a silicon prism, but power is limited (μ Ws) and the system cannot be made portable or robust^[20]. In light of these limitations, IJJs are a compelling alternative because our studies show that a technological pathway exists to significantly improve upon the deficiencies listed above.

2.2 Artificial Josephson Junctions

Investigation of Josephson Junctions as high frequency rf sources began as early as 1994, with the fabrication of an array that successfully functioned in the super-radiation regime at GHz frequencies^[29]. The total output power was 10 μ W and was delivered to a load instead of emitted into free space and detected as radiation. Most rf emission demonstrations have used artificial Josephson Junctions (AJJs)^[4, 30-32], as opposed to the *intrinsic* type we are proposing. The small superconducting energy gap associated with most AJJ materials limits the upper operating frequency to a few tens of GHz and the large junction dimensions require that they be spaced far (integral wavelengths) apart. Such an arrangement not only requires tedious fabrication but limits the strength of the interaction because only a small number ($\sim$ 100) could ever be made to synchronize. Another problem associated with AJJs is that the insulating layer is comprised of a thick, artificially grown amorphous material. When attempting to grow more than one junction (for the purpose of enhancing the THz interaction), their crystalline properties vary dramatically and unpredictably, due to random nature of crystal growth near an amorphous material^[7]. This in turn causes a variation in the individual voltage drops across each structure, preventing synchronization due to a distribution in respective oscillation frequencies.

2.3 Intrinsic Josephson Junctions

Our approach advances the state-of-the-art by taking advantage of the *intrinsic* junction that forms between adjacent layers of certain superconducting materials due to their specific crystal structure^[9]. This scheme allows many such junctions, up to 50,000, to fit into the space of one THz radiation wavelength, and the junctions are geometrically identical because the crystal structure of each layer is dictated by the atomic dimensions of the one beneath it. The intrinsic junction arrangement is crucial because it dramatically enhances the THz interaction over a large spectrum from

0.3 to > 1 THz, enabling a technology path toward practical devices. We have selected the material $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ (BSCCO) as the host crystal because it has a sufficiently large energy gap (60 meV) to enable true THz interaction and because we have proven experience in its fabrication^[33]. Since these structures are small with a moderate heat load, they can be routinely cooled to below the critical temperature of 90K using compact, lightweight (<250g) commercial cryo-cooler modules. We note that this small cryo-cooler would be the largest component of an integrated system.

3. DEVICE DESIGN

Figure 2 schematically depicts a number of Josephson junction layers situated between plate-like leads, together with relevant dimensions and orientation with respect to current flow and the Poynting vector. Note that $L_z \equiv Ns$, where N is the number of junctions and s is the interlayer BSCCO junction width of 1.53nm. For a given frequency of operation, ω_J , the condition $L_x, L_z \leq k_o^{-1} = c / \omega_J$ must be met in order for all junctions to synchronize.

The boundary conditions for the oscillation depend upon the fields outside the stack, which in turn depend upon geometry of the stack and its plate-like leads. We considered the simplest geometry possible, with the only assumptions being 1.) the width of the stack is much longer than a radiation wavelength, i.e., $w \gg k_o^{-1}$, and 2.) the stack is bounded with low-loss metallic contacts (shown in **Figure 2**) with the same lateral sizes (L_x, w) as the stack but extending in the z direction over the distance $L_{sc} \gg k_o^{-1}$. The contacts serve not only as convenient wire-bond locations, but act as radiation screens, restricting emission to the half-infinite spaces of $|x| > L_x / 2$, which greatly enhances radiation by eliminating destructive interference. Because heat dissipation increases linearly with L_x , while output power remains constant, we have chosen a plate-like geometry (i.e., thin in the x -direction) to maximize efficiency. Radiation power and Joule heating were then calculated and dimensions were chosen such that the former is maximized, while the latter is minimized. For a single junction, the quasi-particle dissipation and fluctuations of the Cooper pairs results in a very narrow line width, better than 10^{-5} , in a good agreement with experiment. For the IJJ architecture shown below, we anticipate that line width of radiation will drop inversely proportional to the number of participating junctions such that for $N > 10,000$, $\Delta f \approx 10^{-9}$.

Figure 2. Schematic of intrinsic Josephson junction THz source.

To demonstrate THz emission, we will first compare the IV characteristics of a sample known to be weakly radiating (for example, without radiation screens) with one that strongly radiates. The influence of radiation on the descending branch of the IV curve should be readily apparent. For the geometry depicted in **Figure 2**, radiation power is given by:

$P_{rad} \approx \frac{\pi w}{\omega_J} \left(\frac{J_c s \lambda_c \omega_p^2 N}{2c} \right)^2$, where J_c is the critical current density, λ_c is the London penetration depth along the c -axis, and w is the width of the device. At a conservative dc current bias of $\sim 0.01J_c$, the crystal should radiate with power $P_{rad} / w \approx 30\text{mW/cm}$. By comparing the performance of samples with different numbers of junctions, the N^2 dependence of output power can be confirmed. With the device dimensions listed above, the heat load, $Q \propto 2P_{rad} / L_z w$, should be in the range of 10mW, well within the 350mW cooling capacity of the commercial micro cryo-cooler.

4. RESULTS

A key conclusion of the modeling effort based on the above design is that for the dense junction packing achieved in BSCCO crystals, the localized electromagnetic field (due to Josephson supercurrents) is effective in causing individual junctions to self-synchronize and emit coherently. The process is identical to stimulated emission in a laser, where individual atomic transitions synchronize to form a common quantum coherent state and radiation field^[6]. The fact that IJJ radiated power is proportional to the number of active junctions squared (N^2) is a consequence and confirmation of self-synchronization, as it is a signature of coherence among a system of N harmonic oscillators^[30]. This interaction is achieved only when the junctions are forced from a superconducting state to a resistive state, such that a voltage drop appears across each junction causing the phase of the tunneling current to oscillate with frequency $\omega_J = 2eV_{dc} / \hbar$. This resistive state is most easily achieved by increasing current through the junction stack until reaching the critical current J_c . At that point, the junctions develop a voltage drop and current can be decreased to a value corresponding to the desired emission frequency, with the lower limit set by $V_p \sim \hbar\omega_p / 2e$, where $\omega_p / 2\pi \approx 0.15\text{THz}$ is the Josephson plasma frequency^[34]. For a high purity crystal, the individual junctions are identical and because they are electrically in series with one another, the same voltage drop occurs across each (except perhaps for the outermost layers), establishing among them a uniform oscillation frequency. We predict, as shown in **Figure 3**, a clear difference in IV curves for a sample that is radiating power versus one that is not. *Thus, the routine procedure of obtaining an IV curve can directly provide a method for characterizing radiation power.*

Figure 3. I-V curves of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ (BSCCO) from our analytical model showing junction current j as a function of voltage V with (red, top) and without (blue, bottom) THz emission.

Another crucial conclusion is that the coherent state is preserved not just for a local band of frequencies (as would be the case if a resonant cavity field were responsible for self-synchronization) but for a large span of frequencies, depending upon bias current, extending from approximately 0.5 to at > 1 THz. The analogous situation in a solid-state laser would be the ability to tune the band-gap of the lasing material itself (an intrinsic material property), resulting in a corresponding change in output frequency. This enabling feature makes the IJJ source truly unique because its narrow-band ($\Delta f/f=1\text{e-}9$) signal can be widely and rapidly tuned across the THz region.

5. CONCLUSIONS

We have completed a modeling and design study resulting in specific device geometry with realistic fabrication steps. We have motivated the application of such a THz source and shown that methods exist to initiate, sustain, and measure the radiation process. Furthermore, the emission process is robust to material defects, such that up to ~10% of junctions can be defective without a noticeable effect on emission. Efforts are underway to transition the IJJ design to single crystal BSCCO and initial tests have demonstrated that the dimensions of the active areas of the design are achievable without apparent crystal damage. It is important to note that even with an optimized design many (some unknown) challenges exist for successful demonstration of THz emission using this tunable source approach. BSCCO films with high purity have been grown at Los Alamos and elsewhere in the past, but with the *c*-axis perpendicular to the substrate plane. The *c*-axis of the crystal is perpendicular to the cuprate oxide planes and in order to effectively out-couple radiation and efficiently sink heat from the device, we require that the *c*-axis be grown *parallel* to the substrate. These and other fabrication challenges are beyond the scope of a modeling and design study but did inform the design process, resulting in a device whose structure and dimensions can be realistically achieved using focused ion beam milling, ion etching, and other readily available micro-fabrication techniques.

ACKNOWLEDGMENTS

We gratefully acknowledge the support of the U.S. Department of Energy via the LANL/LDRD Program for this work.

REFERENCES

- [1] Federici, J., Schulkin, B., Huang, F. *et al.*, "THz imaging and sensing for security applications, explosives, weapons and drugs " *Semicond. Sci. Technol.* , 20 (7), S266-S280 (2005).
- [2] Rosker, M., "Opportunities for the Application of Terahertz Technologies in Defense," *SURA THz Applications Symposium*. 1, 16-17 (2004).
- [3] Zhong, H., Redo, A., Chen, Y. *et al.*, "THz wave standoff detection of explosive materials," *Proc. SPIE*. 6212, 62120L-8 (2006).
- [4] Bae, M. H., and Lee, H. J., "Progress in THz generation using Josephson fluxon dynamics in intrinsic junctions," *IEICE Trans. Electron.*, E89-C(2), 106-112 (2006).
- [5] Koshelev, A. E., and Bulaevskii, L. N., "Resonant electromagnetic emission from intrinsic Josephson-junction stacks with laterally modulated Josephson critical current," *Phys. Rev. B*, 77 (1), 014530 (2008).
- [6] Ozyuzer, L., Koshelev, A. E., Kurter, C. *et al.*, "Emission of Coherent THz Radiation from Superconductors," *Science*, 318 (5854), 1291-1293 (2007).
- [7] Bulaevskii, L., and Koshelev, A., "Radiation from Flux Flow in Josephson Junction Structures," *J. Supercon.*, 19 (3), 349-367 (2006).
- [8] Bulaevskii, L. N., and Koshelev, A. E., "Radiation from a Single Josephson Junction into Free Space due to Josephson Oscillations," *Phys. Rev. Lett.*, 97 (26), 267001 (2006).
- [9] Bulaevskii, L. N., and Koshelev, A. E., "Radiation due to Josephson Oscillations in Layered Superconductors," *Phys. Rev. Lett.*, 99 (5), 057002-4 (2007).
- [10] Bulaevskii, L. N., Koshelev, A. E., Maley, M. P. *et al.*, "Radiation from Josephson vortex flow in layered superconductors." *SPIE* 5932, 59320N-14.
- [11] Pedersen, N. F., and Madsen, S., "Search for in-phase Josephson vortex solutions in BSCCO type junctions: modelling and numerical simulations," *Supercond. Sci. Technol.*, 20 (2), S1-S5 (2007).
- [12] Tachiki, M., Iizuka, M., Minami, K. *et al.*, "Emission of continuous coherent terahertz waves with tunable frequency by intrinsic Josephson junctions," *Phys. Rev. B*, 71 (13), 134515-5 (2005).
- [13] Batov, I. E., Jin, X. Y., Shitov, S. V. *et al.*, "Detection of 0.5 THz radiation from intrinsic Bi-2212 Josephson junctions," *Appl. Phys. Lett.*, 88(26), 262504-7 (2006).

- [14] Bulaevskii, L. N., Koshelev, A. E., and Tachiki, M., "Shapiro steps and stimulated radiation of electromagnetic waves due to Josephson oscillations in layered superconductors," *Phys. Rev. B*, 78 (22), 224519 (2008).
- [15] Savel'ev, S., Yampol'skii, V., Rakhmanov, A. *et al.*, "Using Josephson vortex lattices to generate, detect and control THz radiation," *Physica C: Supercond.*, 437-438, 281-284 (2006).
- [16] Takemoto-Kobayashi, J. H., Jackson, C. M., Pettiette-Hall, C. L. *et al.*, "High temperature superconducting monolithic phase shifter," *IEEE Trans. Appl. Supercond.*, 2 (1), 39-44 (1992).
- [17] Zhou, T., Yating, H., Shengnan, Z. *et al.*, "THz radiation sensing and emission: The phase-locking properties of Josephson junction arrays coupled with THz frequency Fabry-Perot resonators," 3rd IEEE Intl. Conf. Nano/Micro Eng. Mol. Syst., NEMS. 3, 1208-1211 (2008).
- [18] Zhou, T. G., Zhou, T. G., Fang, L. *et al.*, "Nonlinear Inductance of Intrinsic Josephson Junction Arrays and Its Application to Tunable Filters," *IEEE Trans. Appl. Supercond.*, 17 (2), 586-589 (2007).
- [19] Josephson, B. D., "Possible new effects in superconductive tunnelling," *Phys. Lett.*, 1 (7), 251-253 (1962).
- [20] Tonouchi, M., "Cutting-edge terahertz technology," *Nat. Photon.*, 1 (2), 97-105 (2007).
- [21] Moore, D., "Recent Advances in Trace Explosives Detection Instrumentation," *Intl. Journ. Sens. and Imag.*, 8 (1), 9-38 (2007).
- [22] DeLucia, F. C., Petkie, D. T., Shelton, R. K. *et al.*, "THz + 'X': a search for new approaches to significant problems," *SPIE*. 5790, 219-230 (2005).
- [23] Gordy, W., and Cook, R. L., [Microwave Molecular Spectra] Wiley, New York, 29-35 (1984).
- [24] Kemp, M. C., Taday, P. F., Bryan, E. C. *et al.*, "Security applications of terahertz technology," *SPIE*. 5070, 44-52 (2003).
- [25] Yunqing, C., Haibo, L., Yanqing, D. *et al.*, "Spectroscopic characterization of explosives in the far-infrared region," *SPIE*. 5411, 1-8 (2004).
- [26] Everitt, H. O., DeLucia, F. C., Bederson, B. *et al.*, [Advances In Atomic, Molecular, and Optical Physics] Academic Press, Boston, 331 (1995).
- [27] Shelton, R., DeLucia, F., and Petkie, D. T., [THz+X Seedling Report] DTIC, No. ARO45655.1, (2006).
- [28] Fitch, M. J., and Osiander, R., "Terahertz Waves for Communications and Sensing," *APL Tech. Digest*, 25 (4), 348-355 (2004).
- [29] Han, S., Bi, B., Zhang, W. *et al.*, "Demonstration of Josephson effect submillimeter wave sources with increased power," *Appl. Phys. Lett.*, 64 (11), 1424-1426 (1994).
- [30] Barbara, P., Cawthorne, A. B., Shitov, S. V. *et al.*, "Stimulated Emission and Amplification in Josephson Junction Arrays," *Phys. Rev. Lett.*, 82 (9), 1963 (1999).
- [31] Kleiner, R., and Müller, P., "Intrinsic Josephson effects in high-temperature superconductors," *Phys. Rev. B*, 49 (2), 1327 (1994).
- [32] Yurgens, A. A., "Intrinsic Josephson junctions: recent developments," *Supercond. Sci. Technol.*, 13 (8), R85-R100 (2000).
- [33] Jia, Q. X., Foltyn, S. R., Arendt, P. N. *et al.*, "High-temperature superconducting thick films with enhanced supercurrent carrying capability," *Appl. Phys. Lett.*, 80 (9), 1601-1603 (2002).
- [34] Latyshev, Y. I., Yamashita, T., Bulaevskii, L. N. *et al.*, "Interlayer Transport of Quasiparticles and Cooper Pairs in 2212 Superconductors," *Phys. Rev. Lett.*, 82 (26), 5345 (1999).