NEWSLETTER

of the International Consortium "Development of High-Power Terahertz Science & Technology"

June 2016 № 3

CONTENT

EDITORIAL: HOW TO CONTRIBUTE TO THE NEWSLETTER

Dear Reader,

As usual, immediately after the publication of the current Newsletter, we are calling for submissions to the next issue and begin collecting relevant information from the institutions participating in the International Consortium for Development of High-Power Terahertz Science and Technology. As already announced in the previous editorials and can be seen in the issues published so far, we are inviting contributions to the following rubrics:

- Research highlights (annotations) presenting the projects pursued by the members of the Consortium.
- Short regular papers.
- Proposals for collaborative research work.
- News from the participating institutions.
- Information about conferences, symposia, workshops, seminars.
- Programs and frameworks for an exchange of visits and mobility of researchers. Job opportunities (especially for young researchers, e.g. postdoctoral positions, specializations, internships).
- Annotations of books, conference proceedings, software and internet resources. Additions to the list of the recent scientific publications and conference reports at the website of the Consortium (http://fir.u-fukui.ac.jp/Website_Consortium/publist.html).
- Information and announcements about awards and nominations.
- Short presentations of laboratories and research groups belonging to the participating institutions.

We believe that this Newsletter could become an essential source of information about our collaborative work on the development of high-power THz science and technology. For this to happen, however, more active participation of the researchers from the member institutions is necessary. We do expect that the number of submissions to the next issues will grow and cordially invite and encourage our colleagues to contribute by sending us any relevant information on the topics listed above.

Since our aim is to facilitate the exchange of information without overloading the contributors with routine technical procedures and details, there are not special requirements concerning the preparation of the submitted materials. Please use MS Word document in Times New Roman text format. The illustrative materials (e.g. photos, figures) are acceptable in any of the commonly used formats (JPG, GIF, TIFF, and PNG). Each submission should begin with a title followed by the names and the affiliations of the authors. The manuscript could be structured as a research paper (divided in sections and subsections and including an abstract, references, acknowledgements, etc.) or as a short note (letter) consisting of one or several paragraphs. There are no strict restrictions concerning the volume of the materials but it is expected that they will be between ½ -1 page for short notes and announcements and 5-8 pages for all other presentations.

Please submit your contributions to the Newsletter as well as requests for information to:

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RESEARCH HIGHLIGHTS

International collaboration as a way to novel THz physics and techniques

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Members of the newly formed International Consortium of THz Photonics and Optoelectronics met in Moscow

The International Consortium of THz Photonics and Optoelectronics was established on 17 December 2015, in Moscow, by 71 partners from 15 countries. A memorandum of understanding (MOU) was signed by the parties. The MOU outlined the intent by the participants to further relations among them to implement international scientific, technological, and educational cooperation related to the properties and possible applications of terahertz (THz) photonics and optoelectronics. The participants agreed to establish long-term partnerships and take concerted actions for joint fundamental and applied research on topics of mutual interest. Among the main goals of the consortium is cooperation in developing a long-term strategy and implementing specific actions aimed at scientific cooperation and coordination of R&D, fostering improved communication and consultation among the members, and assisting in the development of educational programs and publications.

At the Consortium meeting, Professor T. Idehara and Professor M. Glyavin presented reports, related to the development of high-frequency gyrotrons. A nice example of the joint research in powerful THz generation is the development of a novel second harmonic gyrotron with an improved mode selection due to the usage of a dual-beam electron-optical system (EOS).

Recently, a series of CW and pulsed gyrotrons operating in the frequency band 0.2–1.3 THz has been developed. Since the output frequency is close to the cyclotron frequency or its harmonics (and therefore is proportional to the magnetic field intensity in the resonant cavity) the availability of sufficiently strong superconducting magnets is the main limiting factor for a further advancement towards higher frequencies. The most affordable cryomagnets (i.e. having a reasonable cost and appropriate dimensions) are capable of producing a magnetic field with a maximum intensity of about 10–15 T. Thus, in the frequency range 0.7–1.0 THz an operation at harmonics of the cyclotron frequency is inevitable. Such operation, however, is prone to many well-known problems. Among them, the most serious are the lower efficiency of the interaction and the mode competition. In order to overcome the latter a careful mode selection and a suppression of the parasitic modes has to be ensured. For suppression of the competing modes two groups of methods, namely *electron selection* (e.g. using an axis-encircling electron beam, which couples only to the co-rotating modes with an azimuthal index that equals the harmonic number as in the so-called Large Orbit Gyrotron (LOG)) or, alternatively, *electrodynamical selection* (for instance, through an appropriate profiling of the cavity resonator and the field profile inside it). Unfortunately, the first method requires a complicated EOS that forms a uniaxial beam (using a cusp-gun or a kicker) instead of a helical electron beam of a conventional EOS with a magnetron injection gun (MIG). The second method also has a significant drawback because it demands an extremely high accuracy of the manufacturing of the circuit components.

In this project, we explore a promising alternative approach in order to solve the above-mentioned problems. It is based on the usage of a multiple-beam scheme. The previous experience with such systems (see, for example, [V.E. Zapevalov, V.N. Manuilov, O.V. Malygin, Sh.E. Tsimring, "High-power twin-beam gyrotrons operating at the second gyro-frequency harmonic," Radiophysics and Quantum Electronics, **37**, 3, 237-240 (1994)]) has demonstrated that even in the simplest arrangement which uses only one additional electron beam (with a current that amounts to 20-30% of the main beam current) the spurious modes can be suppressed effectively. Moreover, it has been shown that the output power at second harmonic operation can be almost doubled. Here, we extend this concept to the development of THz-range gyrotrons operating in CW regime at the second and third harmonics of the cyclotron frequency and estimate the appropriate operational parameters.

The principle of operation of multi-beam gyrotrons is shown in Fig.1. There are two possibilities to suppress the competing mode. The first one is to use the so-called generating (aka co-generating) beams when both helical electron beams (HEBs) have close values of the pitch-factors ($g_1 \approx g_2 > 1$). The second way is to form an additional HEB with $g_2 << 1$ (the smaller, the better), which can be used for absorbing the power of the parasitic modes at the fundamental, while for the main beam again the condition $g_1 > 1$ is fulfilled.

For a better understanding of the suppression of spurious modes it is instructive to consider the radial dependence of the coupling coefficients $G(R_1)$ and $G(R_2)$ of the operating and the competing modes to the electron beam given by

$$G(R)=\frac{J_{m-s}^{2}(\nu_{m,p}R/R_w)}{(\nu_{m,p}^{2}-m^{2})J_{m}^{2}(\nu_{m,p})}$$

Here, the eigenvalue $\nu_{m,p}$ of the mode $Te_{m,p}$ is the p^th root of the equation $J'_m(\nu)=0$, and R_w is the radius of the waveguide. For the case when both beams are used for generating microwave radiation (g_1, $g_2>1$) it is possible to choose the operating mode and beam radii in such a manner that the radii R_1, R_2 of both thin annular beams correspond to the maxima of the function $G_{op}(R)$ of the desired mode. At the same time, for spurious modes, the values of $G_{par}(R_1)$, $G_{par}(R_2)$ are essentially lower. Obviously, such condition is favorable for a self-excitation of the chosen operating mode. In the case when the additional beam (with $g_2<<1$) plays a role of an absorber, it is possible to provide favorable conditions for the operating mode (i.e. $G_{op}(R_1)$ close to the maximum) while for the additional beam the coupling is small ($G_{op}(R_2)<<G_{op}(R_1)$). At the same time, one should ensure the opposite situation for the parasitic mode, namely its coupling to the main beam with a high pitch factor should be small, while its coupling to the additional absorbing beam should be close to the maximum. As a result, the spurious mode will be suppressed effectively.

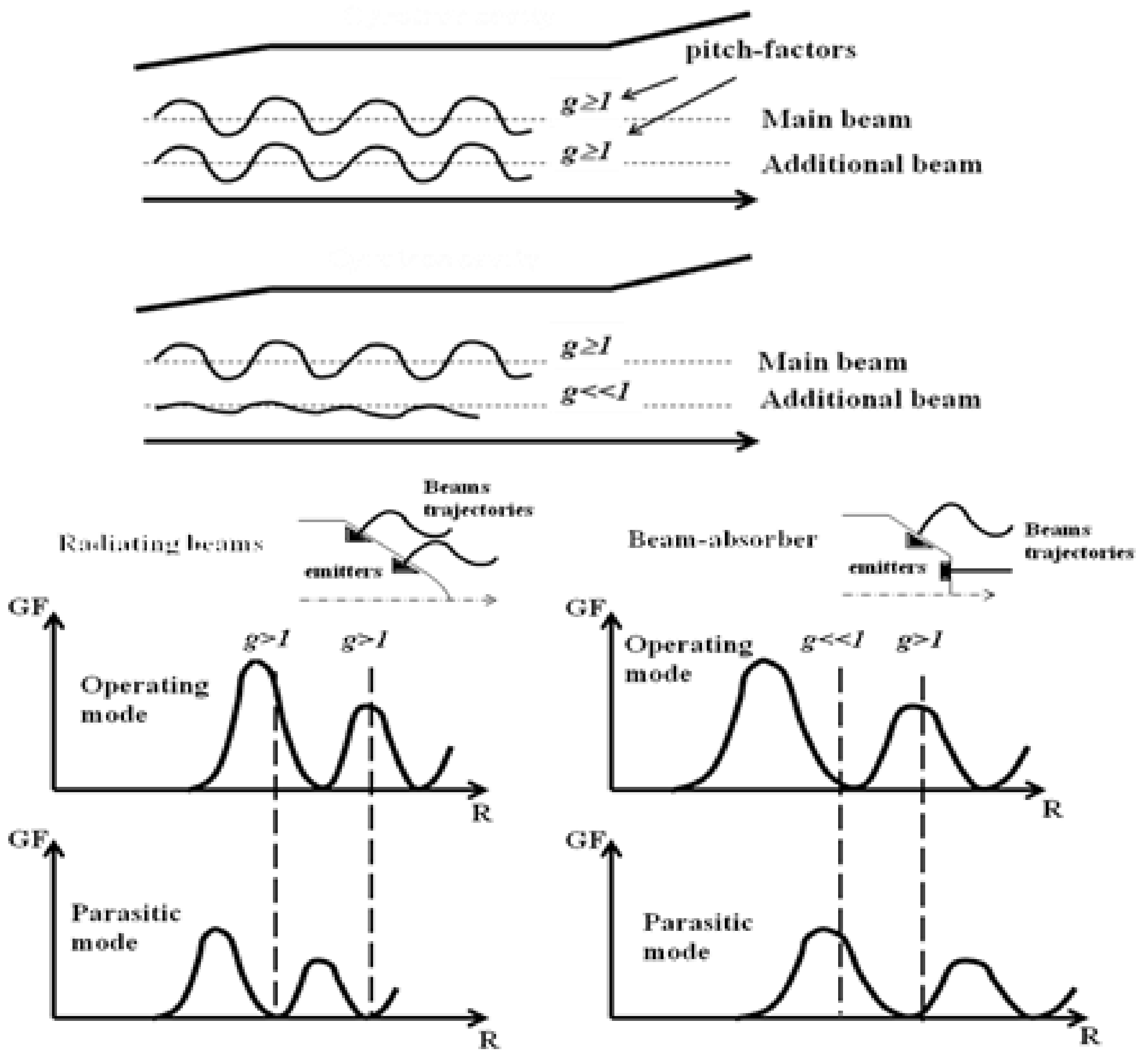

Fig.1 Schematics of multi-beam gyrotrons with either two generating beams or with a generating and an absorbing beams.

The double beam scheme gives a chance to widen the operational parameter space and particularly to increase significantly the beam current and thus the output power of the generated radiation. The starting currents of the main second harmonic mode and these of the most critical parasitic modes at the fundamental harmonic are presented in Fig.2. It can be seen, that for the single beam case (k=0 or k=1, where k is the ratio of the internal beam current and the total current) the starting current of the parasitic mode is approximately two times higher, comparing with the main mode, but for k~0,7 the starting current of any parasitic mode is four times higher than that of the operating one. Therefore, it appears that the preferable case is the one with currents I_{o2}=0.66 A and I_{o1}=0.34 A correspondingly.

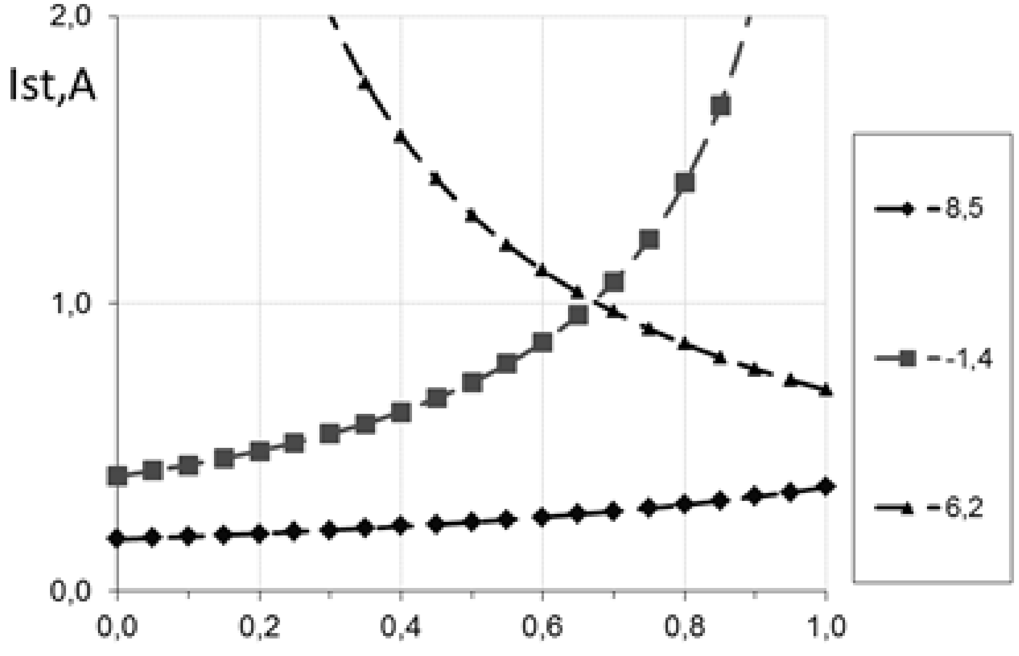

Fig.2. Stating currents for operating and spurious modes as a function of the ratio $k=I_{o2}/I_{tot}$ for the case of two generating beams in the cavity with a total current $I_{tot}=I_{o1}+I_{o2}$ =1 A.

The design of the tube is based on a 15 T liquid helium-free superconducting magnet JMTD15T52 produced by JASTEC Ltd. and utilizes a high-voltage power supply with a fixed operating voltage of 20 kV, and a beam current up to 2 A.

The optimized configuration of MIG electrodes, obtained by EPOS code for the second harmonic $TE_{8,5}$ mode is shown in Fig.3. For numerical analysis of mode excitation and mode competition we use homemade codes and 3D *CST Studio Suite* PIC code. The results of simulations are presented in Fig.4.

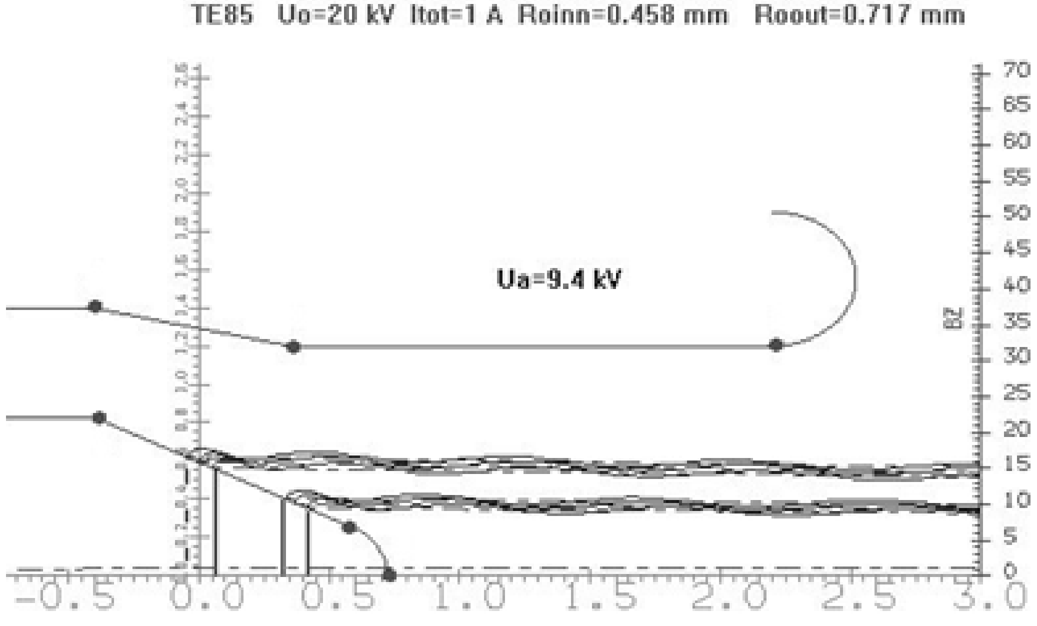

Fig. 3. Geometry of the magnetron injection gun (cathode and anode).

It is seen, that for a beam current of about 2A, at single beam scheme excitation of fundamental parasitic mode has been observed (left column). At the same time, for double beams system with the same parameters, a stable single mode operation at the second harmonic takes place (right column). The analysis shows that the introduction of the additional generating electron beam allows to remarkably increase the operating current up to 2 A with an effective suppression of self-excitation of spurious modes at the fundamental harmonic (Fig.4). The maximum electron efficiency achieves a value of 2.5% with ohmic losses about 80%. The concept makes it possible to achieve the radiation power up to 100-200 W in the single-mode CW regime of generation at the frequency of 0.79 THz. In order to increase the total efficiency, a scheme of energy recovery based on separation of two beams into the collector sections with different decelerating potentials is under discussion.

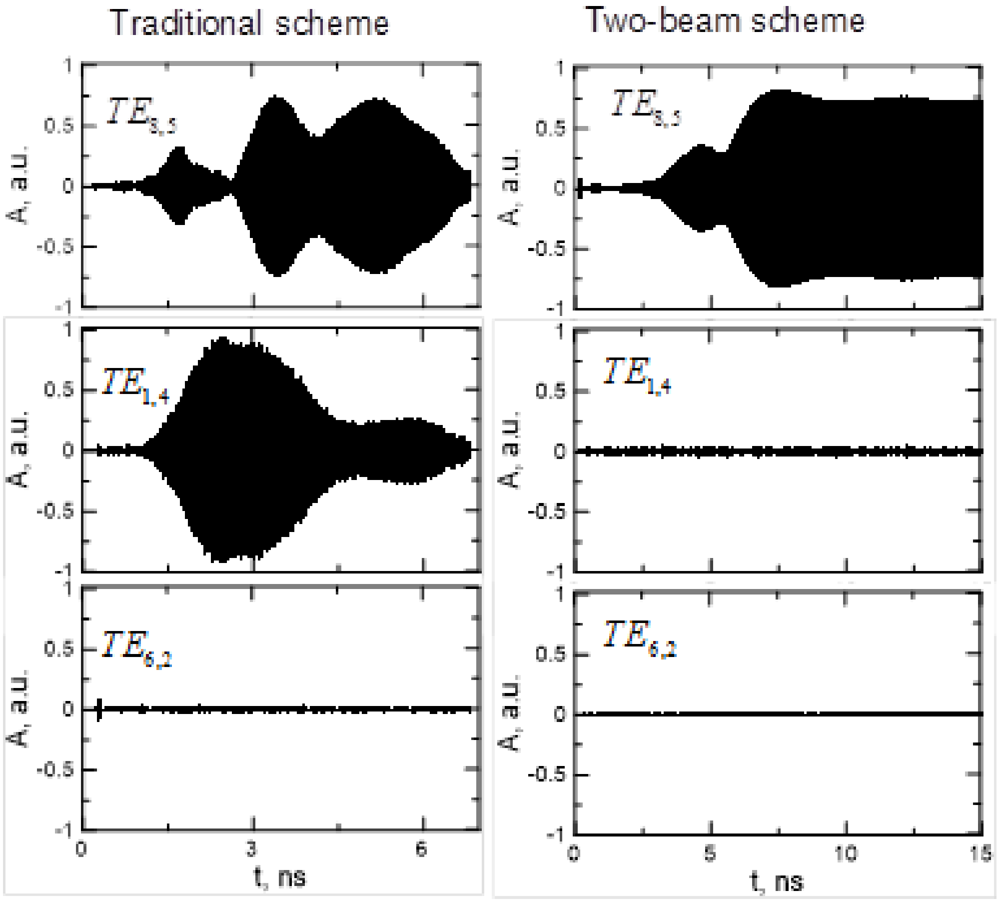

Fig. 4. Start-up scenario of a single beam and a double beam gyrotron.

The MIG has been developed and manufactured by IAP RAS and a demountable tube has been made by FIR UF. The experimental tests of the double-beam gyrotron are planned for the beginning of June 2016. In a case of successful experiments, a novel source for high resolution DNP/NMR spectroscopy with a record frequency will be realized.

References

1. V.N. Manuilov, M.Yu. Glyavin, A.S. Sedov, V.Yu. Zaslavsky, T. Idehara, "Design of a Second Harmonic Double-Beam Continuous Wave Gyrotron with Operating Frequency of 0.79 THz," *Journal of Infrared, Millimeter, and Terahertz Waves*, **36**, 12, 1164-1175 (2015)
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PRESENTING OUR COLLABORATORS

Consortium of Excellence for THz Science and Technology at Tsinghua Optoelectronic Research Interdisciplinary Center (TORIC), National Tsinghua University (NTHU), Taiwan

The current research areas of the center members are as follows:

- High-power Coherent THz generation by tunable injection-seeded FEL for THz Nonlinear Photonics (Y. C. Huang, NTHU)
- Development of Gyrotron-based high-power submillimeter wave sources and applications (T. H. Sam Chang, NTHU)
- Metamaterial (T. J. Yen, NTHU), semiconductor (J. W. Shi, NCU) and Liquid Crystal (R. P. Chao, NCTU) based functional THz photonic elements.
- Multi-service THz Radio-over-fiber communication and sensing network for future ultra-broadband media, data and biomedical applications (C. L. Pan (NTHU), C. K. Sun (NTU), Jin-Wei Shi (NCU), Robin Huang (NTHU), Chi-Wai Chow (NCTU))
- THz and Ultrafast diagnostics for advance materials

Faculty members of the proposed Center of Excellence for THz Science and Technologies are among the world's foremost scientists who advance the state-of-art of THz Science and technology and exploit the unique advantages of terahertz (THz) radiation for various applications. The co-PI also have active international collaborations with groups in the Russian Academy of Sciences, Stanford University, UC Davis, Pisa University, Osaka University and Fukui University, Japan.

The main aim of the center is to provide adequate infrastructures and foster closer collaboration between participating scientists both in Taiwan and abroad. This will be accomplished by setting up, staffing and maintaining state-of-art laboratories as user facilities; funding guest researcher visits and by organizing symposiums and conferences.

For more details please visit the website of the consortium (from which this information is extracted) at:
http://thoric.web.nthu.edu.tw/files/15-1893-66834,c8974-1.php?Lang=en
http://thoric.web.nthu.edu.tw/files/15-1893-94652,c9044-1.php?Lang=zh-tw

IW - FIRT 2017

The 6th International Workshop on Far-Infrared Technologies (IW-FIRT 2017) and The 2nd International Symposium on Development of High Power Terahertz Science and Technology (DHP-TST 2017)

(7-9 March 2017, University of Fukui, Fukui, Japan)

The International Workshops on Far-Infrared Technologies (IW-FIRT) has been held five times in the past: 1999, 2002, 2010, 2012 and 2014. In these workshops it was aimed to discuss the recent development and future directions of far-infrared and terahertz science and technologies with a special emphasis on high power radiation sources in this frequency region and their applications. On the other hand, the first International Symposium on Development of High Power Terahertz Science and Technology (DHP-TST 2013) was held in 2013 for discussion of the development of gyrotrons in sub-THz to THz band and their applications. This symposium was associated with the International Consortium "Promoting International Collaboration for Development and Application of Submillimeter Wave Gyrotrons," which consisted of six overseas institutions and three domestic institutions including FIR UF as the moderator institute. This International Consortium was reorganized and expanded in 2015 to the new International Consortium for "Development of High-Power Terahertz Science and Technology" (Visit: http://fir.u-fukui.ac.jp/Website_Consortium/), which consists of thirteen institutions from the world including FIR UF as the facilitator institute. We feel that it is the time to organize IW-FIRT and DHP-TST as a joint meeting to update our knowledge and understanding in this rapidly developing field. Therefore, we organize the Sixth International Workshop on Far-Infrared Technologies (IW-FIRT 2017) and The 2nd International Symposium on Development of High Power Terahertz Science and Technology (DHP-TST 2017) jointly, rather than organize them separately. An important aspect of this joint meeting is to discuss the present status and future prospect of application of high power terahertz technologies.

The joint workshop and symposium consist of invited talks, oral presentations, a panel discussion and a poster session with the following scope of topics:

1) Development of high power radiation sources in the far-infrared region,
2) Application of high power terahertz technologies especially to the following topics:
   - 2-1) Terahertz spectroscopy;
   - 2-2) Magnetic resonance phenomena in the far-infrared region;
   - 2-3) Material development with high-power FIR sources.
3) Other subjects related to the far-infrared region.

For information about the past workshops of IW-FIRT and DHP-TS please follow the links:

5th IW-FIRT 2014, 4th IW-FIRT 2012, 3rd IW-FIRT 2010, and DHP-TST 2013

For more details please visit the official site of IW-FIRT 2017:
http://fir.u-fukui.ac.jp/IWFIRT/IWFIRT2017/index.html

CONFERENCES

41st International Conference on Infrared, Millimeter and Terahertz Waves, 25-30 September, 2016, Copenhagen, Denmark – Bella Center.
http://www.irmmw-thz2016.org/

The 10th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics - Metamaterials 2016.
The event will comprise a 4-day Conference (19–22 September 2016), and a 2-day Doctoral School (17–18 September 2016) at Via vito volterra 62, Chania, Crete, Greece.
http://congress2016.metamorphose-vi.org/

European Microwave Wek 2016, 3 –7th October 2016, ExCell London, UK (five days and three conferences: The 46th European Microwave Conference (EuMC); The 13th European Radar Conference (EuRAD 2016), and The 11th European Microwave Integrated Circuits Conference (EuMIC). http://www.eumweek.com/conferences/eumc.html

An International Joint Conference of the 9th Global Symposium on Millimeter-Waves (GSMM 2016) and The 7th ESA Workshop on Millimetre-Wave Technology and Applications, June 6-8, 2016, Aalto University, Espoo, Finland.
http://gsmm2016.aalto.fi/

The 9th International Kharkiv Symposium on Physics and Engineering of Microwaves, Millimeter and Sub Millimeter Waves and Workshop on Terahertz Technologies, 20-24 June 2016, Kharkiv, Ukraine.
http://www.msmw.org.ua/

The 16th International Conference on Mathematical Methods in Electromagnetic Theory (MMET 2016), 5-7 July 2016, Lviv, Ukraine.
http://mmet.org/2016/index.php

The 4th Advanced Electromagnetics Symposium (AES 2016), Convention & Exhibition Centre, Torremolinos (Malaga), Spain, July 26, 2016 – July 28, 2016.
http://mysymposia.org/index.php/AES16/AES16

The 9th International Conference on Microwave Materials and Their Applications.
July 3(Sun.)~6(Wed.), 2016, Seoul Olympic Parktel, Seoul, Korea.
http://www.mma2016.org/

IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization for RF, Microwave and Terahertz Applications (NEMO 2016), 27-29 July 2016, Beijing,China.
http://nemo-ieee.org/

International Microwave and Terahertz Technology Conference (ICMTT 2016), 4-5 June, New York, US.
http://theconferences.org/conference/2016/06/new-york/ICMTT

2016 IEEE MTT-S International Microwave Workshop Series onAdvanced Materials and Processes for RF and THz applications, 20-22 July, 2016, Chengdu, China.
http://www.ee.uestc.edu.cn/imws-amp2016/Important_Dates.html

The 3rd Global Congress on Microwave Energy Applications (3rd GCMEA), Cartagena, Spain, July 25-29, 2016.
http://cpcd.upct.es/3gcmea/

Eighteenth edition of the International Conference on Electromagnetics in Advanced Applications (ICEAA 2016) coupled to the sixth edition of the IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (IEEE-APWC 2016), 19-23 September 2016, Cairns, Australia.
http://www.iceaa-offshore.org/j3/

The IEEE and MTT-S International Microwave and RF Conference (IMaRC), 5-9 December, 2016, New Delhi, India.
http://www.imarc-ieee.org/

The 3rd International Conference on Microwave and Terahertz Technology (ICMTT 2017)
2017-03-18~2017-03-20 Bangkok, Thailand.
http://www.aconf.org/en-us/conf_74134.html

2017 IEEE/MTT-S International Microwave Symposium - MTT 2017 (IMS), 4 Jun - 9 Jun 2017, Honololu, HI, USA.
http://ims2017.org/

LIST OF SELECTED RECENT PUBLICATIONS

Bibliography and links to selected recent publications on topics related to the research field of the International Consortium

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NEW BOOKS

A. S. Gilmour, Jr., **Klystrons, Traveling Wave Tubes, Magnetrons, Crossed-Field Amplifiers, and Gyrotrons** (Artech Books).Now available as an e-book:
http://www.asgilmourjr.com/

Clive Poole and Izzat Darwazeh, **Microwave Active Circuit Analysis and Design,**
1st Edition (Elsevier, 2015) Print ISBN 9780124078239 Electronic ISBN 9780124079373.
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Balamati Choudhury, Arya Menon, Rakesh Mohan Jha, **Active Terahertz Metamaterial for Biomedical Applications** (Springer Briefs in Electrical and Computer Engineering, 2016)
ISBN: 978-981-287-792-5 (Print) 978-981-287-793-2 (Online)
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Balamati Choudhury, Bhavani Danana, Rakesh Mohan Jha, **PBG based Terahertz Antenna for Aerospace Applications (**Springer Briefs in Electrical and Computer Engineering, 2016)
ISBN: 978-981-287-801-4 (Print) 978-981-287-802-1 (Online)
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Boon Kok Tan, **Development of Coherent Detector Technologies for Sub-Millimetre Wave Astronomy Observations (**Springer Theses,2016)
ISBN: 978-3-319-19362-5 (Print) 978-3-319-19363-2 (Online)
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ISBN: 978-3-319-23626-1 (Print) 978-3-319-23627-8 (Online)
http://link.springer.com/book/10.1007/978-3-319-23627-8

NEWS FROM THE NET (OUR BROADER HORIZONTS)

Terahertz radiation has a great potential for Medical Advancements
During the 7th International THz-Bio Workshop, which was held in Seoul, Korea on April 6-8 the latest research advancements on the beneficial biological effects of terahertz radiation were presented and discussed (http://www.thzbioworkshop2016.com/). The main topic this year was: "THz-Bio: Challenges and Opportunities for Industrialization." For more detail, please visit:
http://www.businesskorea.co.kr/english/news/sciencetech/14571-terahertz-paradigm-terahertz-radiation-shows-great-promise-medical

Light-induced superconductivity
Intense light pulses irradiating a sample of K_3C_{60} result in dramatic changes of its high-frequency (terahertz) conductivity.
Demsar Jure, "Emergent phenomena: Light-induced superconductivity," Nature Physics, vol.12, no. 3 (2016) 202-203. DOI: 10.1038/nphys3687.
http://www.nature.com/nphys/journal/v12/n3/full/nphys3687.html

Researchers from Brown University's School of Engineering have developed a new metal lens for focusing terahertz radiation
An array of stacked 32 metal plates, each 100 microns thick with a 1-millimeter space between each plate

is used to make a novel lens for focusing terahertz radiation. The new device has several advantages over the existing Teflon lenses and can easily be calibrated for specific terahertz wavelengths by changing the distance between the plates.
Mendis R., Nagai M., Wang Y., Karl N., Mittleman D.M., Terahertz Artificial Dielectric Lens, Scientific Reports, vol. 6 (2016) 23023. DOI: 10.1038/srep23023. Open Access:
http://www.nature.com/articles/srep23023

3-D printer creates a terahertz lens that could be used for security imaging and biomedical research
A 3D terahertz gradient-refractive index lens designed by transformation optics is achieved by fabricating "woodpile" structures with varying dimensions of subwavelength dielectric unit cells using the projection microstereolithography technique. Both simulation and experimental investigations confirm that the lens delivers an imaging resolution very close to the diffraction limit over a frequency range **from 0.4 to 0.6 THz**.
http://onlinelibrary.wiley.com/doi/10.1002/adom.201600033/abstract

'Color' photography at terahertz frequencies
The developed novel solid-state-based sensors can be operated at room temperature for spectroscopic THz imaging purposes. THz photographs at different frequencies have been obtained demonstrating that it is possible to determine the chemical composition of packaged samples if their spectra are known a priori.
http://spie.org/newsroom/6285-color-photography-at-terahertz-frequencies

New compact terahertz radiation source that operates at room temperature continuous wave (CW) for sensing applications.
The device is based on nonlinear mixing in quantum cascade lasers. The system achieved room-temperature CW emission at 3.41 THz with and output power up to 14 μW.
Lu Q., Wu D., Sengupta S., Slivken S., Razeghi M., Room temperature continuous wave, monolithic tunable THz sources based on highly efficient mid-infrared quantum cascade lasers, Scientific Reports, vol. 6 (2016) 3595. DOI: 10.1038/srep23595. Open Access:
http://www.nature.com/articles/srep23595

Physicists discover new state of the water molecule
The novel, so-called tunneling form of water has been created in narrow channels in beryl. It is believed, however, that this state probably happens often in nature but it is difficult to be detected with the available techniques.
http://physicsworld.com/cws/article/news/2016/may/06/physicists-discover-new-state-of-the-water-molecule
See the original paper: Kolesnikov A.I., Reiter G.F., Choudhury N., Prisk T.R., Mamontov E., Podlesnyak A., Ehlers G., Seel A.G., Wesolowski D.J., Anovit, L., "Quantum Tunneling of Water in Beryl: A New State of the Water Molecule," *Phys. Rev. Lett.*, 116 (2016) 167802. DOI: 10.1103/PhysRevLett.116.167802.
http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.167802

UMD Researchers Make Breakthrough in Terahertz Technology
A University of Maryland (UMD) research team, in collaboration with Monash University and the United States Naval Research Laboratory, has invented a Tunable Large Area Hybrid Metal-Graphene Terahertz Detector, an innovation based upon a successful demonstration of plasmonic resonance in graphene micro-ribbons that are connected to metal electrodes, offering a critical step toward practical graphene terahertz optoelectronic devices. The invention has been nominated by UMD's Office of Technology Commercialization for the Invention of the Year award in the Physical Sciences category.
http://www.scienceandtechnologyresearchnews.com/umd-researchers-make-breakthrough-terahertz-technology/