NEWSLETTER

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Professor Masahiko Tani
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FIR UF
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sabch@ie.bas.bg

INVITED PAPERS

Breakthrough to high-power continuous-wave terahertz generation: a 250-Watts, 0.5-THz second-harmonic gyrotron

M. Yu. Glyavin, G. G. Denisov

Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod, 603950, Russia

***Abstract*:** To cover the so-called terahertz gap in powerful sources of coherent electromagnetic waves, a second-harmonic gyrotron operating in a 10 T liquid helium-free superconducting magnet has been designed, manufactured, and tested. With an operating voltage of 15 kV and a beam current of 0.6 A, the gyrotron generated coherent continuous-wave radiation at a frequency of 0.526 THz with an output power of 250 W and an efficiency of 2.7%. This result is based on the common efforts of IAP RAS/GYCOM team and the full list of authors is presented in the paper published at Electr. Dev. Lett. Journal (doi: 10.1109/LED.2021.3113022).

The development of compact, simple and reliable sources of terahertz (THz) radiation is important for numerous applications. Unfortunately, strong magnetic fields are required to ensure the conditions for cyclotron resonance between rotating electrons and fast waves at THz frequencies: about 36 T is needed for the generation of 1 THz at the fundamental resonance. The typical magnetic field of commercially available cryo-magnets with a sufficiently large warm bore (50–100 mm) does not exceed 15 T; therefore, operation at the second harmonic is required to achieve 0.5 THz. A number of second-harmonic gyrotrons developed for spectroscopy experimentally demonstrated an output power of 10 to 40 W in the 0.4–0.5 THz frequency range [1, 2]. Below we present the design, manufacture, and experimental testing of a gyrotron based on a 10 T helium-free magnet Jastec JMTD 10T100, in which coherent radiation of 0.526 THz was obtained at a record power level of 250 W.

A well-proven gyrotron of the sub-terahertz range at the fundamental harmonic with a radiation frequency of 0.263 THz [3] was taken as the basis for the development of a 0.526-THz tube at the second harmonic. The $TE_{-6,5}$ mode, which had been successfully used earlier for stable single-mode excitation at the second harmonic at lower frequencies, was chosen as the operating mode. We also considered the whispering gallery modes such as $TE_{11,p}$ and $TE_{14,p}$, used in gyrotrons with similar frequencies [2,3], however, numerical calculations predicted better conditions for the excitation of the $TE_{-6,5}$ mode (in particular, a higher beam-wave coupling factor to reduce the operating current). The radius of the guiding centers of the electron beam is 0.87 mm, with a cavity radius of 1.988 mm. In this case, we were able to use the same triode magnetron injection gun developed for a 0.263-THz tube. The electrodes' geometry was selected so that the nominal parameters of the electron flux were achieved in the diode mode (the insulated anode has a ground potential). By varying the anode potential, it is possible to adjust the beam parameters in a wide range of magnetic fields and cathode voltages. The position of the electrodes in the magnetic field was slightly changed compared with the 0.263-THz tube: the distance from the emitter to the center of the solenoid is 374 mm, in contrast to 354 mm in the initial version. Such a shift had virtually no effect on the parameters of the electron beam: in accordance with numerical simulation, the pitch factor of electrons (the ratio between rotational and axial electron velocities) is 1.4, and the root mean square velocity spread is about 8% with allowance for the initial thermal velocities and roughness of the emitter. These values look good enough to achieve high efficiency of the interaction between the electron beam and the cavity mode.

The cavity length was optimized to obtain efficiency close to the maximum for a range of pitch factors from 1.2 to 1.4. According to the calculations, a uniform section length of 20 mm was chosen for a nominal accelerating voltage of 15 kV and a beam current of 0.4 to 0.6 A. The cavity was made of copper; its diffractive and Ohmic Q-factors are estimated as 63000 and 10400, respectively. High precision (fractions of a micron) of the cavity fabrication, high surface quality, and the absence of taper or ellipticity are required in the considered frequency range [4]

The conventional mechanical processing techniques did not provide a sufficient manufacturing accuracy, and the output power did not exceed several watts in the initial experiments. The most successful version of the cavity employed in the experiments was manufactured using ultra-precision turning technology using carbide cutters.

A quasi-optical converter that transforms the operating mode into a Gaussian beam has been developed to extract radiation from the vacuum volume of the gyrotron. The simulation results showed a conversion efficiency of 98.4%. The mode converter consists of a Vlasov launcher, a parabolic mirror, and four correcting mirrors. The surface depth of the profiled mirrors is about 1 mm, which is acceptable for precision manufacturing. Photos of the experimental setup with the tube inside a cryomagnet are shown in Figure 1.

Fig. 1. Photo of the gyrotron and an experimental setup with the tube inside a cryomagnet.

The output power of the gyrotron was measured with a water calorimeter. A study of the excitation of oscillations in the vicinity of the operating mode is shown in Fig. 2a. The area of excitation of the operating mode at the second harmonic is clearly seen; parasitic modes are excited at the fundamental harmonic on the right and left of this area. By varying the magnitude of the magnetic field, the optimal conditions for stable excitation of single-mode oscillation were found. We obtained a maximum output power of 250 W for a beam voltage of 15 kV and a beam current of 0.6 A, which corresponds to an output efficiency of 2.7%. Considering the ratio of diffractive and Ohmic Q-factors, this value corresponds to an interaction efficiency of about 30%, consistent with theoretical estimates for a reasonable value of the pitch factor about 1.2–1.3. The difference between interaction and output efficiency is defined by the Ohmic losses in the cavity, which are about 85%. By varying the beam current, the output power of the gyrotron can be smoothly adjusted from maximum to tending to zero. Figure 2b shows the results of experiments on measuring the radiation power at the second harmonic for an operating current of 590 mA. The conditions for excitation of the operating mode were studied experimentally to determine the minimum starting current. Excitation of the mode at low beam currents was monitored by two methods, namely, observation of the temperature trace of the wave beam passing in a continuous-wave mode through a dielectric plate and measurement of the signal from a high-frequency detector. The measured starting current is 20 mA, which agrees with the calculations and confirms the sufficiently high accuracy of the cavity fabrication and acceptable parameters of the electron beam.

The amplitude-phase structure of the wave beam field was reconstructed using measurements of the intensity distributions in several cross-sections with an infrared camera. The analysis showed that the content of the $TEM_{0,0}$ mode in the output radiation is 62% (see Fig. 3). The most probable reason for the distortion of the wave beam is the insufficient accuracy of the mutual installation of the elements of the quasi-optical converter.

To correct the structure of the output radiation and focus it into a spot, we designed an additional matching optical unit (MOU) consisting of two mirrors with synthesized profiles. According to the simulation results, this unit converts the gyrotron radiation into a Gaussian beam with a calculated half-width at the focal point of 1.1mm / 1.1mm (by the 1/e level of the intensity) and a $TEM_{0,0}$ mode content of more than 98%, while the energy loss for conversion does not exceed 4%.

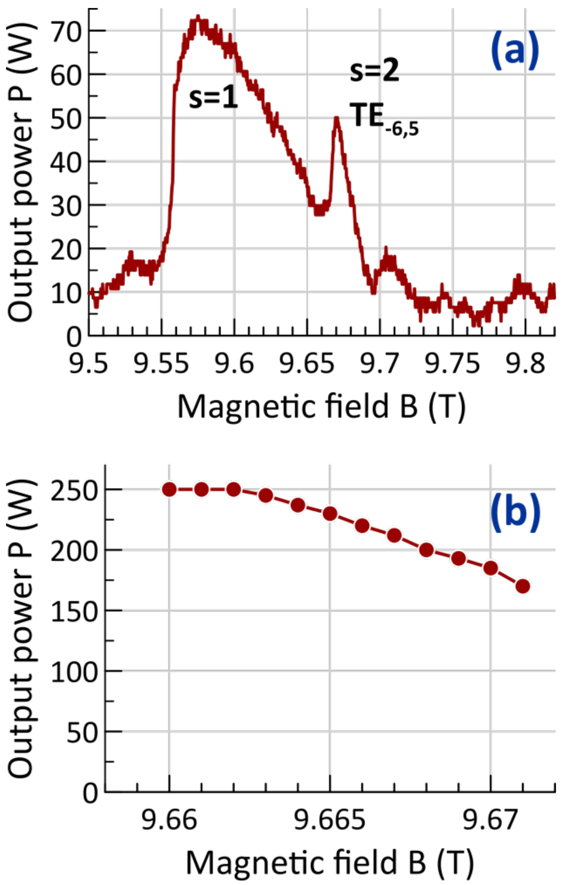

Fig. 2. Output power versus magnetic field: a) generation zones for the operating mode at the second cyclotron harmonic $TE_{-6,5}$ and the nearest parasitic mode, accelerating voltage U = 15 kV and beam current I = 0.4 A; b) $TE_{-6,5}$ output power at U = 15 kV and I = 0.59 A.

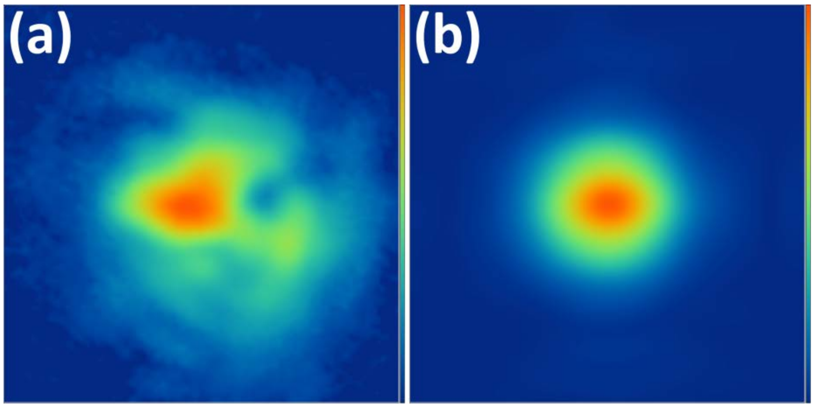

Fig. 3. Transverse distributions of the gyrotron wave beam intensity at a distance of 216 mm from the window: a) measured and b) calculated. Aperture size is 50 x 50 mm.

Frequency measurements were the key to the experimental campaign. For the initial frequency estimation, we used a Fabry-Perot resonator, which allowed us to determine the frequency with accuracy on the order of a gigahertz and to determine the harmonic number accurately. Next, a spectrum analyzer with an external mixer was employed to refine the frequency more accurately and measure the signal spectrum. As an additional check and determination of the presence of radiation impurities with a frequency corresponding to the first harmonic, we used the scheme with scattering by a diffraction grating. The sawtooth-shaped corrugated aluminium plate with a period of 0.6 mm and angles of 30° and 60° at the base has more than 99% of 0.526 THz power reflected into -1st order (reflection angle 14° to the normal) for an incidence angle of 45°. We found no significant intensity peaks at other angles. Therefore, the operating frequency was determined as 0.526 THz without the admixture of parasitic frequencies (parasitic modes).

Thus, in the experiment with a continuous-wave gyrotron at the second harmonic with a cylindrical cavity, coherent radiation with a frequency of 0.526 THz and an output power of 250 W was obtained. This power level looks almost an order of magnitude higher than in the previous experiments.

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Study of 3D-Printed Dielectric Barrier Windows for Microwave Applications

M. D. Proyavin, D. I. Sobolev, V. V. Parshin, V. I. Belousov, S. V. Mishakin, M. Yu. Glyavin

Institute of Applied Physics of the Russian Academy of Sciences, 603950, Nizhny Novgorod, Russia

Abstract: 3D printing technologies offer significant advantages over conventional manufacturing technologies for objects with complicated shapes. This technology provides the potential to easily manufacture barrier windows with a low reflection in a wide frequency band. Several 3D printing methods were examined for this purpose, and the dielectric properties of the various types of materials used for 3D printing were experimentally studied in the frequency range 26–190 GHz. These measurements show that the styrene-butadiene-styrene and polyamide plastics are suitable for broadband low-reflection windows for low-to-medium-power microwave applications. Two barrier windows with optimized surface shapes were printed and tested. The results demonstrate that the studied technique can fabricate windows with a reflection level below −18 dB in the frequency band up to 160 GHz. The studied windows can be used for spectroscopic tasks and other wideband microwave applications.

Additive manufacturing technologies have great potential for industry, science, and technology. There are a number of tasks that are difficult or almost impossible to implement with traditional fabrication methods. In particular, 3D printing from dielectric materials is a highly convenient and cheap tool for prototyping and manufacturing radiofrequency components. It creates a method of readily obtaining components with a sophisticated surface shape. For low-reflection microwave windows, a subwavelength grating with a specially designed shape at both sides of the window disk could significantly reduce the reflection coefficient of incident radiation in a wide frequency band. This paper explores the possibility of using 3D printing to make millimeter-wave barrier windows that can operate in a wide frequency range.

Currently, there are several areas in which windows with the broadband transmission of low-power microwave radiation are used. These areas include, in particular, molecular gas spectroscopy and DNP/NMR spectroscopy, measurements of fine positronium structure, radiometers and geophysical instruments used for atmospheric transparency studies. For all the mentioned applications, the radiation power does not exceed a few watts, which allows one to use windows made of polymers without the risk of overheating.

There are different methods to obtain the broadband transmission of microwave radiation through the windows. The almost reflectionless transmission of a linearly polarized wave can be achieved for the Brewster-angle disk, however, this output suffers from an inefficient use of space, which may be especially important for divergent wave beams and some distortion of the transverse field structure. Polymers can be mixed with nanoparticles to produce a multilayer dielectric coating. Metamaterial devices and gradient index photonic structures are also used to reduce the reflection. Another known method considered in this paper is the use of windows with a surface grating of a specially optimized shape, providing a significant reduction in reflection. For the manufacture of such a surface, it is highly convenient to use 3D printing. Besides low cost and time consumption, 3D printing has no restrictions on the curvature of the surface compared to Computerized Numerical Control (CNC) machining. Furthermore, it has advantages in creating thin elements from relatively soft and brittle materials.

Currently, many different materials for 3D printing are presented on the market, and their number is constantly growing. Unfortunately, manufacturers usually do not provide information on the dielectric properties of materials, especially in the microwave, millimeter, and terahertz regions. In order to design the microwave components, the dielectric properties are of great importance, so the characterization of the materials used for additive manufacturing is needed.

To study the loss tangent and dielectric constant of the plastics, two independent methods were used to increase the reliability of the results. In the first method, a rod made of the investigated plastic was inserted into a rectangular waveguide. The reflection and transmission coefficients were measured, and the dielectric properties were calculated from the experimentally obtained frequency dependences. Formulas for reflection and transmission of the dielectric waveguide plug can be found in [1]. The second method for measuring the properties of dielectrics was to place samples in the form of flat disks between the mirrors of a high-quality open two-mirror Fabry-Perot resonator. By measuring the quality factor of an empty cavity and a cavity with a dielectric insert, it is possible to measure the properties of the test sample with high accuracy [2]. These measurements were made for selected materials and frequencies up to 200 GHz.

For the experimental study of the broadband windows prototypes, we chose SLS printing from polyamide due to low losses and high manufacturing accuracy, which allow the creation of small-scale structures suitable for devices operating at frequencies of several hundred GHz. The sizes of the subwavelength antireflection structures were chosen to produce fine details by the selected printing method adequately. These structures should perform well when half of the wavelength is bigger than the period of the structure because there could be no ±1st order diffraction scattering in these conditions. However, the performance at higher frequencies might degrade faster or slower depending on the shape of the elements. This paper considers the two variants of known antireflection subwavelength gratings at window disks for additive manufacturing. The first variant of the surface shape is a periodic array of pyramids with a base size smaller than the wavelength [3]. The shape of the pyramidal grating is shown in Figure 1a. The advantages of such a surface are a weak dependence of the reflection coefficient on the frequency and polarization of the incident radiation. The base side of the pyramids was chosen to be 1 mm, and the height was 2 mm. Simulations show that this corrugation applied to both surfaces of the polyamide window disk and provided reflections of less than −20 dB in the frequency band wider than one octave. For comparison, the flat polyamide disk had reflections of up to −9 dB in this band. The second option is a one-dimensional periodic corrugation of a special shape, proposed in [4]. This profile is optimized to minimize the reflection of the polarization with the direction of the electric field orthogonal to the groove direction at the frequency range of 60–160 GHz. The shape of the grooves is shown in Figure 1b. The period and depth of one-dimensional corrugation are 2 mm and 2.5 mm, respectively. The corrugation profile was optimized for one linear polarization only, and the reflection coefficient was less than −20 dB for frequencies below 105 GHz.

Three discs were printed: the first one had a flat surface on both sides, the other two had gratings of the tested shape on both sides. The reflection coefficients were obtained by two measurement setups by a vector network analyzer with a step of 30 MHz in the bands of 75–110 GHz and 130–160 GHz, where the disks with optimized surface shapes calculated reflection minima. The window disks were attached to the output of the corrugated tapers providing the Gaussian wave beam flat phase front (Figure 2a). The 0-dB level of the setup was set using the flat mirror closing the end of the taper, and the minimum sensitivity limit was set as the reflection from the open end of the taper.

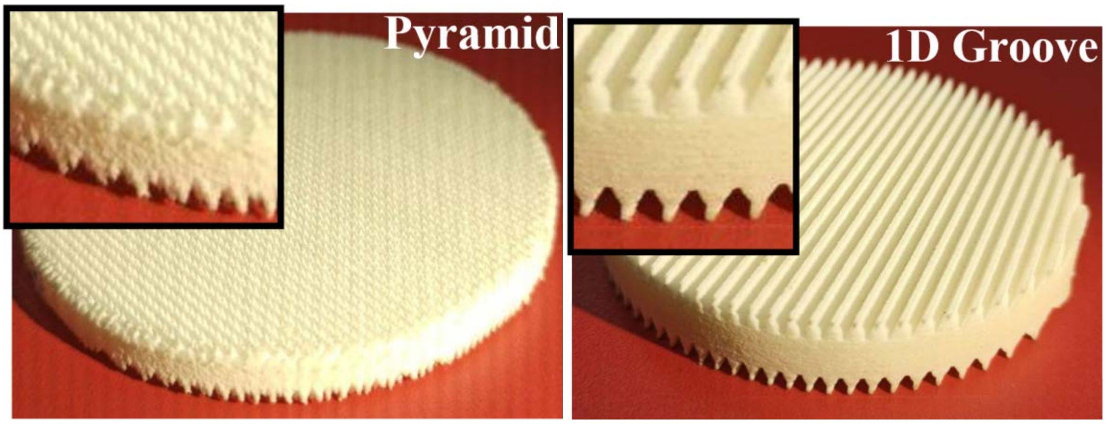

Fig. 1. 3D-printed windows with (a) pyramids; (b) one-dimensional grating of special shape.

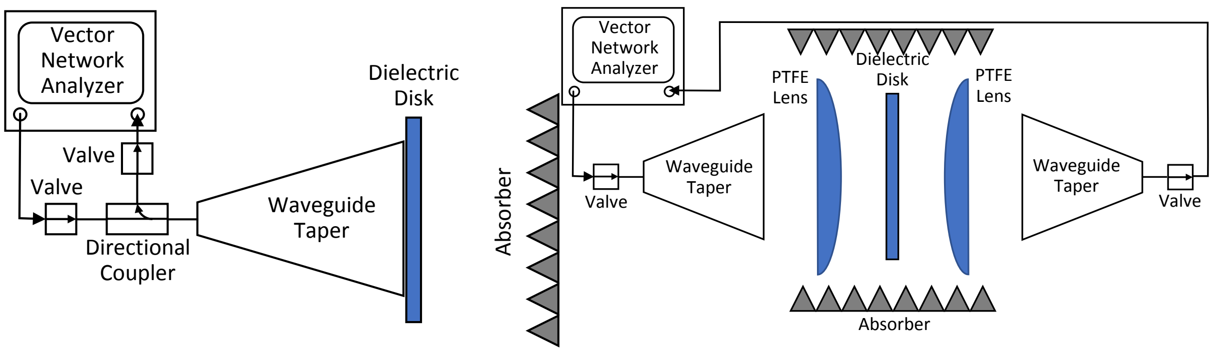

Fig. 2. Schematics of the setups used to measure the dielectric disks parameters: (a) reflection measurements; (b) transmission measurements.

Reflection measurement results are shown in Figures 3-5 for the flat-surface disk, disk with pyramids, and disk with one-dimensional corrugation, correspondingly. The disk with a one-dimensional corrugation of the surface was measured for both orthogonal linear polarizations. However, the results for the second polarization are significantly worse than for the optimal polarization. The measured reflection coefficient is below −18 dB for both corrugated disks in the frequency ranges of 75–110 GHz and 130–160 GHz. In contrast, the flat disk has a much narrower band with low reflections (10 GHz at the level of −20 dB). Note that the option with pyramids is more advantageous if radiation of arbitrary polarization is required, while the option with one-dimensional corrugation is better for specific linear polarization. The one-dimensional corrugation works better for lower frequencies but (due to its larger period) is worse for higher frequencies. Due to the high sensitivity of this shape to manufacturing tolerances, the measured reflection of one-dimensional corrugation significantly deviates from the calculated one, which is also noted in [5].

To measure wideband transmission, we used a quasi-optical setup consisting of a vector network analyzer (VNA), a pair of tapers with PTFE lenses on adaptors, and an air gap between them (Figure 4b). Disks were placed in the center of the air gap, which is also the position of the Gaussian beam waist. The transmission through the two thinner disks is presented in Figure 8. The flat disk has a thickness of 3.15 mm, and the average thickness of the disk with pyramids is 3.33 mm. The low-reflection disk has a significantly better transmission and is very close to the maximum transmission predicted using the measured loss tangent of the polyamide. The disk with one-dimensional corrugation is not shown because it has high dielectric losses in this frequency band due to its bigger average thickness of 7.5 mm. The oscillations of the flat-sided disk transmission are caused by Fabry–Perot resonances inside the disk (period approximately 30 GHz) and resonances between the disk and one of the lenses (approximately 4 GHz). The reflection from the tapers causes fast oscillations (approximately 1 GHz).

To measure wideband transmission, we used a quasi-optical setup consisting of a vector network analyzer (VNA), a pair of tapers with PTFE lenses on adaptors, and an air gap between them (Figure 4b). Disks were placed in the center of the air gap, which is also the position of the Gaussian beam waist. The transmission through the two thinner disks is presented in Figure 6. The flat disk has a thickness of 3.15 mm, and the average thickness of the disk with pyramids is 3.33 mm. The low-reflection disk has a significantly better transmission and is very close to the maximum transmission predicted using the measured loss tangent of the polyamide. The disk with one-dimensional corrugation is not shown because it has high dielectric losses in this frequency band due to its bigger average thickness of 7.5 mm. The oscillations of the flat-sided disk transmission are caused by Fabry–Perot resonances inside the disk (period approximately 30 GHz) and resonances between the disk and one of the lenses (approximately 4 GHz). The reflection from the tapers causes fast oscillations (approximately 1 GHz).

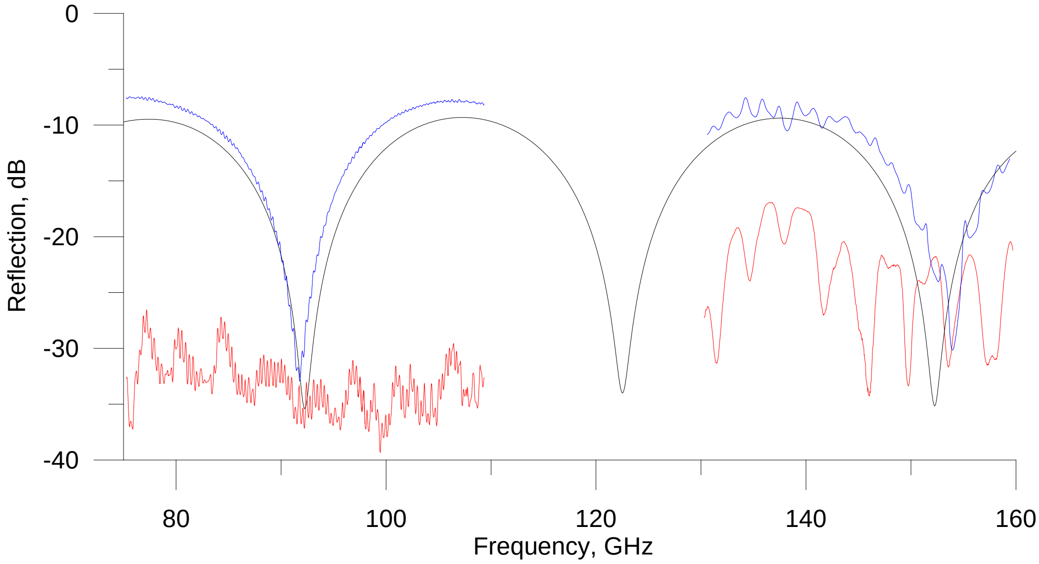

Fig. 3. Reflection from the 3D-printed disk with a flat surface on both sides. The black line corresponds to the numerical simulation in CST Studio. The blue line is the measured reflection coefficient, and the red line is the lower sensitivity limit of the measurement setup.

Based on the obtained values of the real and imaginary parts of the dielectric permittivity, as well as the mechanical and thermal parameters of the tested materials given in [20], it is possible to determine the losses and temperature conditions of a window that can withstand atmospheric pressure, depending on its diameter and the supplied microwave power. When considering the heat problem, the transverse dependence of the microwave radiation intensity on the radius was taken as a Gaussian wave beam with a width of 0.64 of the window radius. Numerical modeling was performed with the following parameters to represent many plastics with similar properties: n = 1.5, emissivity ε = 0.9, and the thermal conductivity of plastic κ = 0.4 $W\cdot m^{-1}K^{-1}$. The dielectric loss tangent was taken as slightly larger than the best-tested plastic δ = 0.002. The temperature of the cooled edge of the window (ambient temperature) was T_0 = 20 °C, with a convection coefficient of h = 10 $W\cdot m^{-2}\cdot K^{-1}$. Several window diameters were considered between 1 cm and 10 cm with different thicknesses from 1 mm to 10 mm, and the wavelength was set as λ_0 = 3 mm, which corresponded to the 100 GHz base frequency. Dielectric losses are proportional to the frequency; therefore, the maximum power for any other frequency can be calculated by multiplying the ratio of the base frequency to the target frequency. Numerical modeling of the dielectric disk heating by a Gaussian beam was performed in COMSOL Multiphysics. The reflections of the beam on disk surfaces were neglected, assuming the antireflection surfaces. We simulated maximum beam power, which can be transmitted through the disk, given that the maximum stationary temperature is 120 °C, so a disk with diameter 100 mm and thickness 10 mm can withstand approximately 150 W of CW transmitted power at a frequency of 100 GHz without convective cooling.

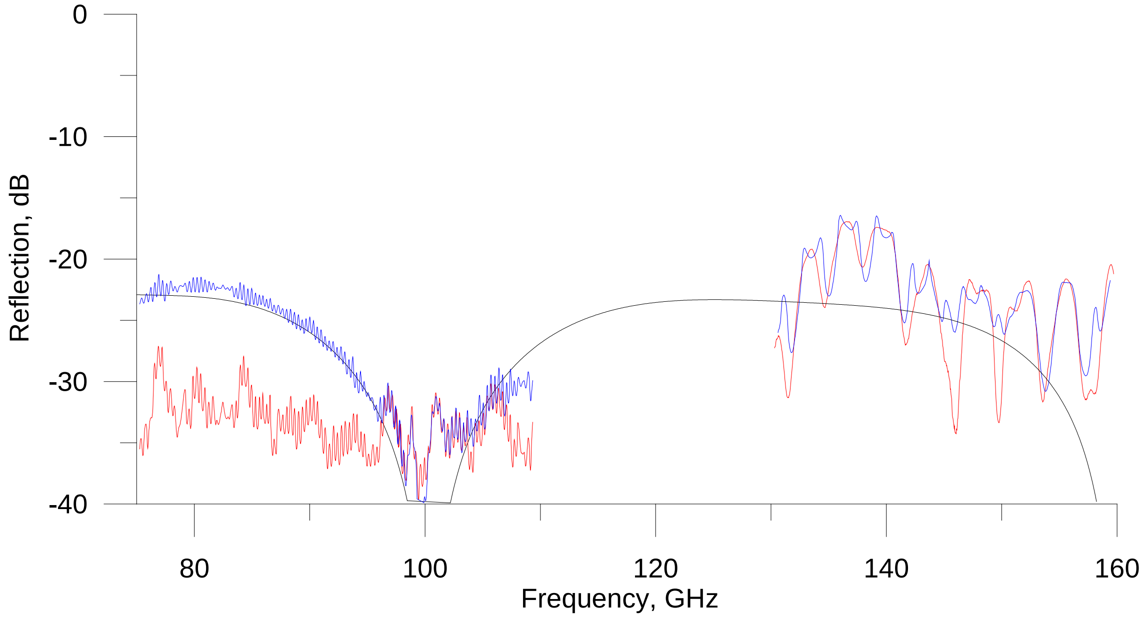

Figure 4. Reflection from the 3D-printed disk with pyramids on both sides. The black line corresponds to the numerical simulation in CST Studio. The blue line is the measured reflection coefficient, and the red line is the lower sensitivity limit of the measurement setup.

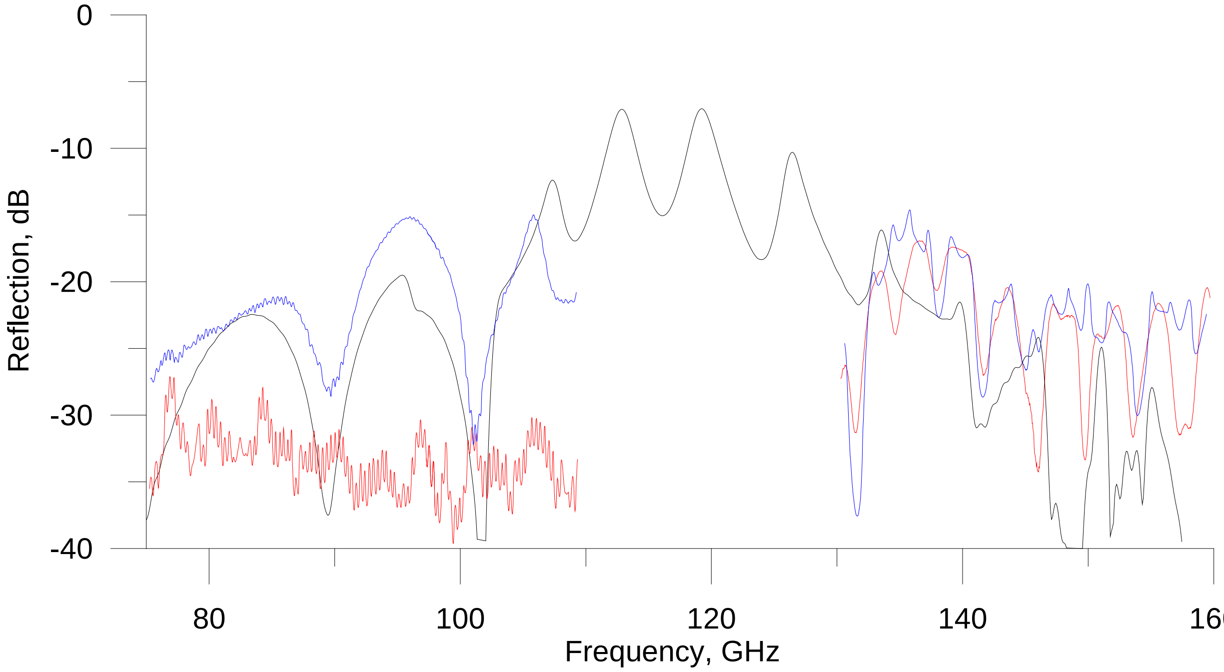

Fig. 5. Reflection from the 3D-printed disk with special one-dimensional corrugation on both sides. The black line corresponds to the numerical simulation in CST Studio. The blue line is the measured reflection coefficient, and the red line is the lower sensitivity limit of the measurement setup.

Current 3D printing technologies allow easy-to-manufacture dielectric microwave components, such as broadband barrier windows with low reflections. In this paper, the dielectric properties of the materials used in various 3D printing methods were measured. The most suitable materials were found to be useful in microwave systems with a frequency of up to several hundred gigahertz and a power of up to several tens of watts. The analytical calculations and numerical simulations verify the use of the studied materials for microwave devices with a power of about 100–200 watts.

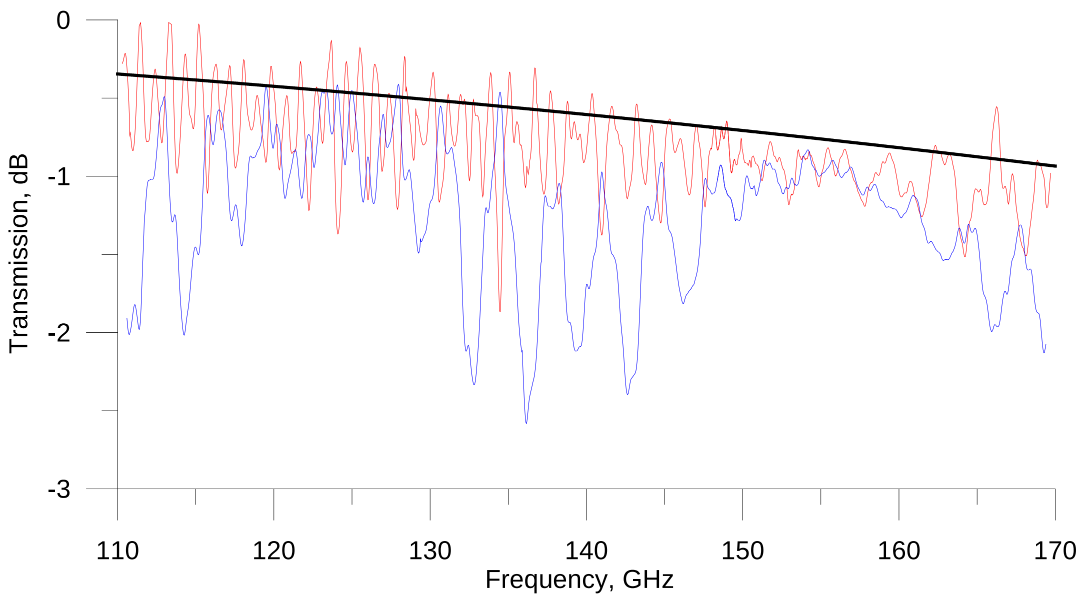

Fig. 6. Transmission through the disks. The red line corresponds to the disk with pyramids on both sides, and the blue line corresponds to the flat-surface disk. The black line shows dielectric losses calculated in the 3.33 mm thick polyamide disk with zero reflections.

Barrier windows with surface shapes specially optimized for low reflection in a wide frequency band were printed and examined at low power. The printed windows provided a reflection coefficient below −18 dB at frequencies of up to 160 GHz, making it possible to use in microwave devices that require the reception/transmission of a signal in a wide frequency range. We conclude that the current additive technologies are competitive with traditional manufacturing methods for dielectric microwave components at 1 millimeter and for longer waves.

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Regimes of Hybrid Modes in a THz Clinotron

Eduard Khutoryan[1, 2], Alexei Kuleshov[1, 2], Sergey Ponomarenko[1], Konstantin Lukin[1], Yoshinori Tatematsu[2], Masahiko Tani[2]

[1] *O. Ya. Usikov Institute for Radiophysics and Electronics of NAS of Ukraine*
12 ac. Proskura str., Kharkiv, Ukraine, 61085
[2] *Research Center for Development of Far-Infrared Region, University of Fukui,*
3-9-1 Bunkyo, Fukui-shi, Fukui, Japan, 910-8507
e-mail: jeanalexkh@gmail.com

Existing and potential applications of THz radiation in physics, biology, chemistry, medicine, imaging, spectroscopy, etc. require compact radiation sources with sufficient output power and frequency tuning range. Although a gyrotron is powerful source in the THz range, slow-wave vacuum electron devices have a great potential for such applications due to their compactness. However, advance of these devices in the THz range is hampered by a confinement of RF field near slow wave system, high-frequency ohmic losses, technological limits, necessity of high-density beams and high focusing magnetic fields, the decrease of the efficiency of output waveguides, etc. Our previous study has showed that the so-called hybrid bulk-surface mode is very promising to enhance the beam-wave interaction efficiency and the output power of THz BWOs and clinotrons. The hybrid bulk-surface wave appears in the cavity with non-uniform (periodically modified) grating. One of the eigenmodes of an open non-uniform grating is a leaky wave, which contains both the wave, radiating into free space and the surface wave confined to the grating surface (surface plasmon polariton) and propagating along a grating. Placing a metal wall above the grating causes reflections of the radiating wave back to the grating with further coupling of the radiating wave to the surface plasmon polariton. Since the reflected radiating wave is confined in the cavity volume (being transformed into a bulk cavity wave) and is coupled with a surface plasmon polariton, such hybrid mode is bulk-surface one. The results of theoretical study are presented below and demonstrate classification of these hybrid regimes in the clinotron oscillator of 0.5-0.7 THz frequency range. To provide efficient output radiation, searching for optimized feedback loop, position and dimension of the output waveguide, grating profile, etc. have been carried out by simulations using the PIC code MAGIC2D.

The variety of oscillation regimes may be roughly described by mutual velocities of the bulk and surface waves, total group velocity, hybridization factor, etc. From those dispersions shown in Fig. 1, one can distinguish several regimes that can be realized by the proper electron beam voltage and a set of the waveguide parameters:

- (*A*) Bulk wave radiation angle is close to 90^{o} to the grating, like in DRO and orotron. Due to the surface wave, the area of $v_{gr} \cong 0$ is much wider than for pure bulk fast mode;
- (*B*) Bulk wave is radiated at the angle $120\text{-}150^{o}$ to the grating (i.e. propagates oppositely to a beam) and therefore, a feedback is provided by the backward radiating harmonic;
- (*C*) Similar to (*B*) but the radiating angle is close to 180^{o} to the grating that resembles Zennek-Sommerfeld wave;
- (*D*) Surface wave propagates oppositely to a beam and the bulk wave; feedback is provided by the backward surface wave.

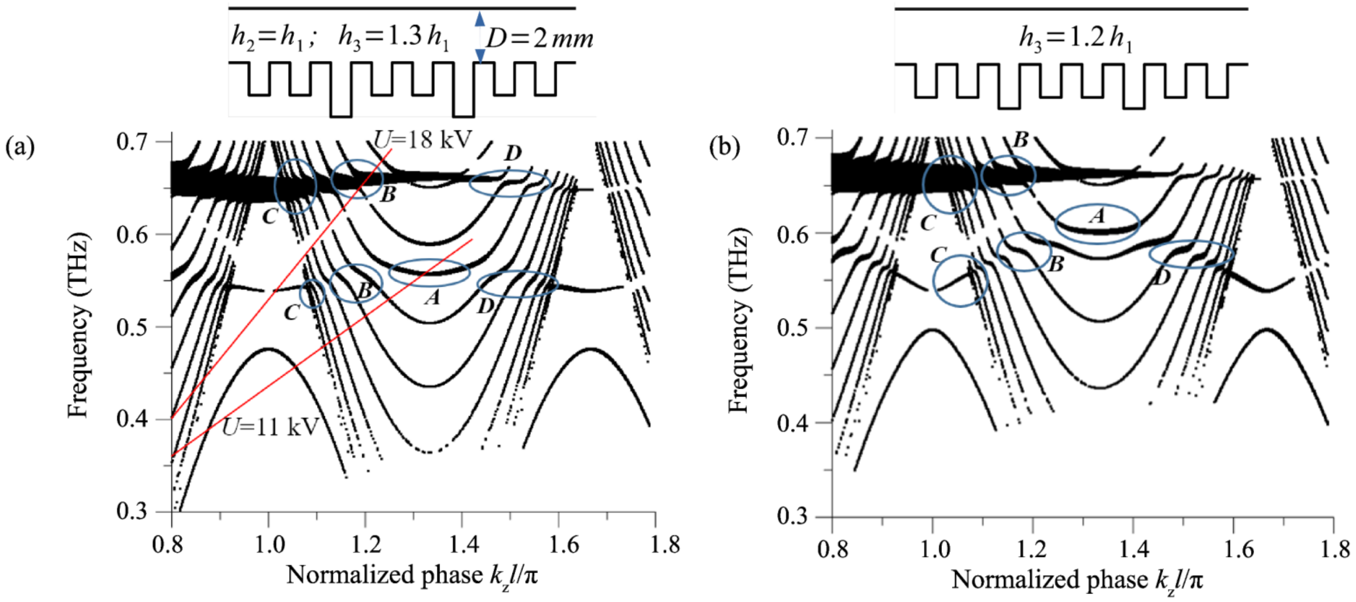

Fig. 1. Dispersions of waveguides containing gratings with period l = 0.07 mm, and a regular groove depth h1 = 0.09 mm, D = 2 mm. (a) h3 = 1.3h1, h2 = h1; (b) h3 = 1.2 h1, h2 = h1. Areas A-D correspond to different regimes of the hybrid mode.

In the regime of bulk wave (-2nd spatial harmonic) the radiation is almost normal to the grating as in devices based on Smith-Purcell radiation such as orotron. The feedback in such regime may be due to multiple reflections from the upper wall (as in an open resonator of an orotron), due to reflections from side walls and due to the backward direction of the bulk wave. Continuous frequency tuning range in this regime is defined by the dispersion curve marked as *A* in Fig. 1 (a), where an increase of the oscillation frequency corresponds to an increase of the radiation angle from normal and, hence, results in the excitation of higher order axial modes (HOAM).

In the Regime *B*, according to the dispersion, the radiation angle is within 120-150°. Here, the feedback is due to the backward bulk wave that is demonstrated by field patterns for *D* = 8 mm (Fig. 2).

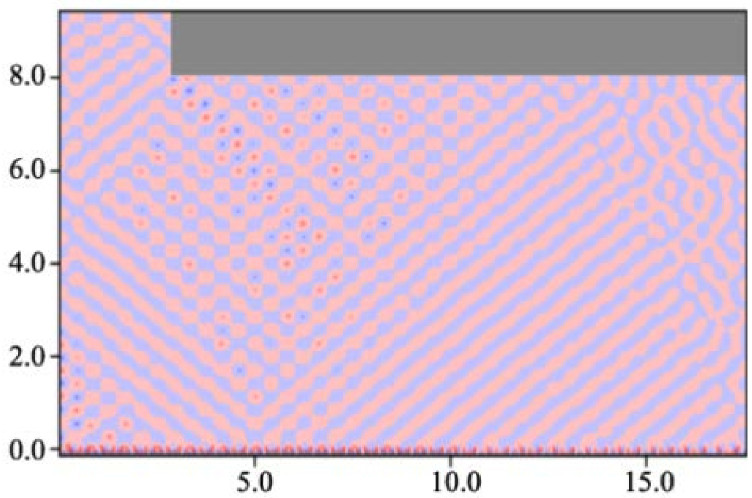

Fig. 2. RF field pattern at steady state demonstrating bulk wave and output radiation propagation.

The length of feedback L_{fb} depends on the radiation angle and the waveguide height *D*. Simulation demonstrated that in the case when L_{fb} is longer than the grating length L_g: $L_{fb} > L_g$, oscillations drop (at L_g = 17 mm and *U* = 19 kV it holds for *D* ≅ 10 mm). In our simulation the coupling hole is placed at the vicinity of z =

0 due to the backward wave nature. The rays responsible for the feedback are only these being reflected from the upper wall to the grating (rays that are reflected to the side wall are idle). Therefore, removing the part of the upper wall $L_{out} = D \tan\alpha$ (from which rays fall on the side wall), does not have any effect on the beam-wave interaction and this size of the coupling hole is close to the optimal value. The bulk wave is a reason of both efficient feedback and effective radiation output, whereas surface wave is a reason of high beam coupling impedance. This fact was proven in the simulation of the case when the middle part of the grating was shortened but the oscillation still existed and resembled two-cavity klystron with coupling between cavities.

At the large radiation angle which is close to 180^o (Regime *C*), there is almost no role of the upper reflector for the feedback by the backward radiating harmonic. Thus, the interaction power P_{int} almost independent from *D* that was proven by hot simulations. In simulations, 22 kV beam excited the oscillation with the interaction power of about 200 W at 0.625 THz. The feedback here is also due to the backward radiating harmonic, which has relatively low loss and provides quite uniform RF field distribution along grating, and, hence, all electron layers effectively interact with the wave. The wave with radiation angle close to 180^o matches well with Zennek-Sommerfeld wave of the flat metal surface and this wave is responsible for a feedback. The considered oscillator is non-resonance BWO. Resonance is possible when reflectors are placed at grating ends that creates an open (without upper wall) or closed resonator. The flat mirrors inclined 5^o to grating enabled an increase of the interaction power about 1.5 times.

Conclusion

The higher output power of the hybrid mode in comparison with pure surface or bulk modes is due to an increase of the feedback and efficiency of the radiation output caused by radiating harmonic, and due to high coupling factor caused by the surface harmonic. 2D PIC simulations predicted output power of dozens of Watts in 0.5-0.7 THz range provided by the 0.2 A, 17 kV electron beam with the output efficiency of up to 1%. The simulated frequency tuning range was about 5%. Mode competition has been discussed, in particular, it is shown that single or two mode operation, hysteresis effect, etc. are controlled by the waveguide height.

For more detail, please access the original publication (Khutoryan E., Kuleshov A., Ponomarenko S. et al., “Efficient Excitation of Hybrid Modes in a THz Clinotron,” J Infrared Millimeter, and Terahertz Waves, vol. 42 (2021) 671–683. DOI:10.1007/s10762-021-00800-y.) as well as the following research papers:

1. S. S. Ponomarenko et al., "Traveling-Wave Amplification in a Circuit With Nonuniform Grating," in IEEE Transactions on Electron Devices, vol. 68, n. 10 (2021) 5232-5237. DOI: 10.1109/TED.2021.3105951.

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sabch@ie.bas.bg

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Message from the Guest Editor

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- **Systems**: Emitter-receiver systems, imaging systems, RF and microwave integrated circuits, diagnostic and therapeutic systems, implantable and wearable diagnostic and therapeutic systems
- **Spectroscopy**: Interaction between THz waves and all states of matter including THz spectroscopy on solids, liquids, gases, and plasmas
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- **Computational methods for bioelectromagnetics**

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Special Issue: Sensing and Imaging with Electromagnetic Waves

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Guest Editor

Dr. Reza K. Amineh

Department of Electrical and Computer Engineering, New York Institute of Technology, NY 10023, USA
Email: rkhalaja@nyit.edu

Manuscript Topics

Sensing and imaging with electromagnetic waves has grown rapidly in the past few decades thanks to the significant progress in the hardware components and processing algorithms. On the hardware side, the emergence of new and cost-effective sensors and their associated data acquisition boards has paved the way toward numerous novel applications. On the processing side, the development of faster computing machines has allowed for realization of more sophisticated algorithms that facilitate real-time or quasi real-time imaging and sensing of the media. The range of applications is very broad and encompass frequencies from fractions of Hertz to tera-Hertz and beyond, including but not limited to: Eddy current inspections, inductive sensing of conductive objects, capacitive sensing of dielectric objects, microwave imaging for biomedical and nondestructive testing applications, microwave sensing for material identification, radar imaging and remote sensing, tera-Hertz imaging and sensing, and optical imaging and sensing. The objective of this Special Issue is to provide an overview of the current research on methods and applications of electromagnetic waves in imaging and sensing of media, highlighting the latest developments and innovations in modern applications in terms of sensors, data acquisition circuits, sampling methods, algorithms, and so on. We will also try to identify new challenges and opportunities for new applications.

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All manuscripts will be peer-reviewed before their acceptance for publication. The deadline for manuscript submission is 15 May 2022.

LIST OF SELECTED RECENT PUBLICATIONS

Bibliography and links to selected recent publications on topics related to the research field of the International Consortium and published after June 2021, i.e. after issuing the previous Newsletter #18. This cumulative list is in chronological order as collected from various bibliographical and alert services

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NEW BOOKS

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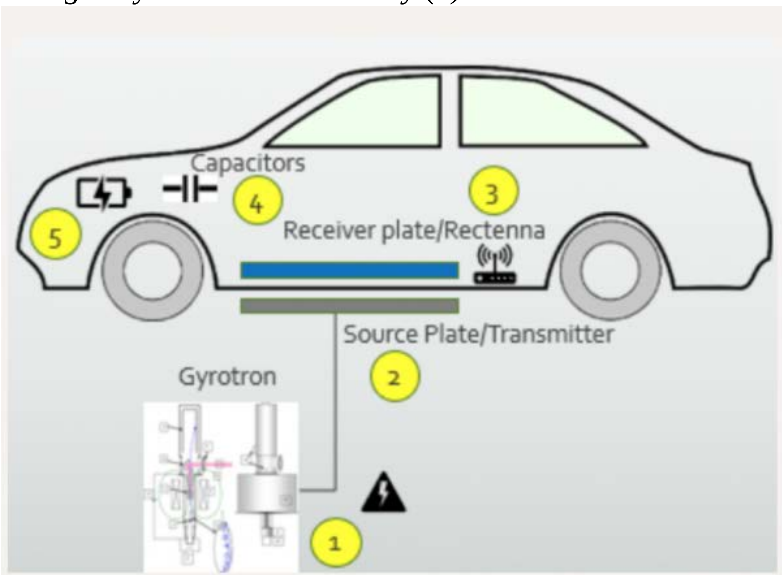
NEWS FROM THE NET (OUR BROADER HORIZONS)

The gyrotrons and the Future of Electric Vehicles (EVs)

In a recent posting by Mark Alexander in RICOCHET a new concept of superfast-charging electric vehicles using gyrotrons has been announced. The author writes" *Imagine a world where EVs can be HyperfastCharged™ 1,000 times faster than current technology. Instead of charging your Tesla or other EV for an hour every 200 miles or so, you can simply drive over a "charging zone" and get a full charge in seconds. In small towns, charging zones could be located at stop signs or service stations. This would relieve range anxiety for many potential EV customers.As you may know, within the next couple of years, autonomous, self-driving long-haul freight trucks will be a reality. Imagine autonomous driverless trucks driving freeways in an EV lane with a HyperfastCharged™ zone every 100 miles. Long-haul trucks could be driving 24 hours per day, minus loading and unloading stops.*" According to Mark Alexander "*The key material component is the gyrotron (1), a powerful beam-based technology that can transmit incredible bursts of energy. For the working prototype, a $500,000+ gyrotron will be purchased. A custom transmitter plate and a receiver plate/rectenna will be created (2) (3). The gyrotron and transmitter plate will be placed below the road surface, creating the HyperfastCharged™ charging zone, and the receiver plate installed on a modified EV, connected to special capacitors (4) that would charge any standard EV battery (5).*"



Schematics of the technology. Figure courtesy RICOSHET

Finally, Andersen concludes: *"This technology offers another approach that, when demonstrated, can be a game-changer. For those of you interested in the research related to the viability of using a gyrotron in this way, see the research review on "Wireless power transfer via Subterahertz-wave" written in 2018 by Sei Mizojiri and Kohei Shimamura.*

Scientists Obtain Magnetic Nanopowder for 6G Technology

News Wise reports: "Material scientists have developed a fast method for producing epsilon iron oxide and demonstrated its promise for next-generation communications devices. Its outstanding magnetic properties make it one of the most coveted materials, such as for the upcoming 6G generation of communication devices and for durable magnetic recording. The work was published in the *Journal of Materials Chemistry C*, a journal of the Royal Society of Chemistry.

Future prospects for microwave drilling in geothermal exploration

Recently, there is a growing interest in the microwave drilling (including such based on gyrotrons) for geothermal energy exploration. Some news on the topic can be found in the following publications:

- "U.S. drilling technology startup Quaise Inc. has started testing of its potentially disruptive drilling technology initially developed at MIT." (follow the link)
- "New technology closer to reaching superhot geothermal energy sources." (follow the link).
- "Progressing towards geothermal energy's holy grail." (follow the link)

Gyrotron Technology Inc. (GTI) Files Patent for Novel Method of Compacting Airbags

GTI, an industrial process technology company, has filed a patent application for a novel method of compacting airbags. This new method utilizes the gyrotron, a very powerful source of high-frequency microwave energy. The method allows direct heating of the cushion material without heating the mold, resulting in very significant shortening of cycle time and substantial reduction of energy usage.

For more details, please visit the link.