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STUDYING SIMILARITY OF SHAPES VIA TERAHERTZ EMISSION SPECTROSCOPY: THE CASE OF UKRAINIAN AND LITHUANIAN SYMBOLS

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In this paper, the thermal emission from the n-GaAs/GaAs structure equipped with the Ti/Au metasurface is being investigated in the terahertz region. The metacell shape was chosen to be of heraldic origin, that is either the Ukrainian Trident or the Lithuanian Columns of Gediminids. The experiments were performed using far-infrared Fourier spectroscopy, where the heated sample served as the source of THz radiation. The optical properties of such structures were simulated using the rigorous coupled wave analysis method in order to explain the origin of experimentally observed spectral features. The deconstruction of the simulated spectra was also performed by simulating the properties of simplified metacells which constitute the metacells of the heraldic symbols investigated here. The spectral analysis suggests the similarity between the investigated symbols, which is also reviewed from the historical point of view.

Keywords: GaAs, metasurfaces, terahertz spectroscopy, magnetic polaritons

1. Introduction

Metasurfaces used in optics promise a plethora of ways of light manipulation [1, 2]. Due to their sub-wavelength dimensions, it is a technologically challenging task to use metasurfaces in the visible range. Therefore, their properties are investigated and applications are demonstrated mostly in mid-infrared or terahertz regions [3–6], where the size of the metacell can be in the micrometre range, allowing processing compatible with conventional UV lithography techniques. As an example, the concept of tailoring the broad spectrum of thermal radiation by employing the metasurfaces could be applied for the production of inexpensive narrow-band infrared and terahertz sources [7–9]. Recently, our group has proposed a terahertz source based solely on GaAs technology, widely used in terahertz photonics [10]. The metasurfaces there are combined from the metallic square-shaped metacells and due to the resonant excitations of magnetic polaritons (MPs) can radiate in a narrowband in the frequencies up to 3 THz. Indeed, the metacells, where MPs are excited, can be of various complex shapes, allowing for an unlimited number of combinations to pick from.

In this article, we have chosen to investigate magnetic polariton excitation related thermal emission from the structures equipped with metasurfaces composed of metacells of the shape of the Ukrainian Trident and the Lithuanian Columns of Gediminids in terahertz (THz) frequency. The reason for our choice is that Lithuania and

Ukraine, situated in the continent of Europe, possess a rich tapestry of shared historical, cultural and geopolitical connections. One of the most significant bonds that link these two nations is their intertwined history of statehood, characterized by once belonging to the Grand Duchy of Lithuania. The Columns of Gediminids (CG) stand as one of Lithuania's oldest enduring national symbols, proudly represented in its historical coats of arms. Records confirm that the Columns of Gediminids were unquestionably featured on the Coat of Arms of Grand Duke Vytautas of Lithuania as early as 1397 [11, 12]. Over the centuries, multiple theories about the origin of this symbol have emerged. While the local, indigenous origin has gained prominence in recent times, ideas suggesting Genoa (Italy), Tatar, Scandinavian [12] or even Ancient Greek [13] origins have also been proposed. The Coat of Arms of Ukraine consists of a blue shield adorned with a prominent golden trident. It is formally known as the Emblem of the Royal State of Volodymyr the Great [14] and is informally referred to as the 'tryzub' (Ukrainian: тризуб, meaning 'trident') (TR). While archaeologists have discovered examples of tridents on the Ukrainian territory dating as far back as the 1st century AD, the origins of this symbol can be traced to the trident depicted on the golden coin issued by Volodymyr the Great, the first Grand Prince of Kyiv [15]. There are also claims suggesting that the Columns of Gediminids may have evolved from the Ukrainian Trident [12] through the symbol of the Rurikids [16].

2. Methods

In this work, the thermal THz emitters composed of n-GaAs/GaAs structures were investigated. The structure consisted of a 525 μm thick n-type GaAs substrate layer on which, using the molecular beam epitaxy (MBE) technique, an undoped 4.3 μm thick GaAs spacer layer was grown. Periodic 0.2 μm thick Ti/Au metasurfaces were formed using maskless UV laser lithography and the lift-off process of e-beam sputtered thin metal films. The image of fabricated metasurfaces is seen in Fig. 1(a). There were two samples with a different geometrical shape of a metacell: Columns of Gediminids (bottom) and Trident (top). The former one has 45 × 45 μm dimensions of a structure with a metacell size of 55 × 55 μm, and the latter has a cell size of 61 × 51 μm and structure dimensions of 46 × 41 μm. Since the Trident in the official Coat of Arms of Ukraine is quite complex, we chose a simplified historical variant of the Trident found on the coins of the Kievan Rus'. The need of simplifying the metacell arises from the fact that a large amount of small similar-sized details of a metacell would lead to a large amount of high frequency and relatively weak peaks in the spectrum. As for the Columns of Gediminids, we also chose a variant that could be easily transformed into a metacell.

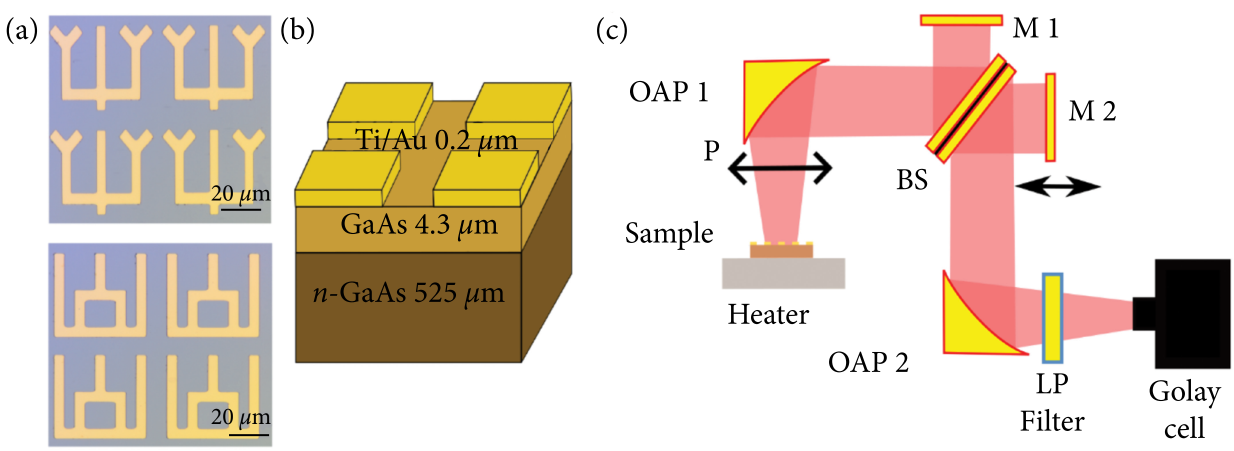

Fig. 1. (a) The microscopic photos of the metasurfaces produced the Trident (top) and The Columns of Gediminids (bottom); (b) the structure of the samples consists of a 525 μm-thick n-type GaAs substrate layer, a 4.3 μm-thick GaAs spacer layer and a 0.2 μm-thick Ti/Au metasurface layer; (c) the experimental setup of a Fourier spectrometer. Here P denotes a polarizer, OAP is an off-axis parabolic mirror, M is a flat mirror, BS is a beamsplitter, and LP filter is a low-pass filter.

For the experimental emission measurements, a custom-made Fourier transform infrared (FTIR) spectrometer (Fig. 1(c)) placed in a metallic vacuum box, also providing the screening of external electromagnetic fields, was employed. Samples were mounted on an electrically controlled external heater and heated up to around 240°C. In order to reduce the unwanted background signal the samples were covered with a 2 mm diameter conical output aperture. A low-pass filter was used to reduce the detection of radiation above 4 THz. A chopper was employed to modulate the signal at 23 Hz for the lock-in amplifier and the Golay cell was used as a detector. Three measurements for each sample were done: without a polarizer (P), for s-polarization and p-polarization. The open-source Python-based rigorous coupled wave analysis (RCWA) code [17] was modified and used to perform the simulations of the optical properties of metasurfaces with the aforementioned geometry using the dimensions and structure of the fabricated n-GaAs/GaAs/Ti/Au samples. The simulations performed showed the reflectivity and emissivity spectra of the samples for two perpendicular polarizations.

3. Results and discussion

The system of metal/insulator/metal ($\mu < 0$, $\varepsilon > 0$) and conductive plane layer ($\mu > 0$, $\varepsilon < 0$) reflecting the structure of the samples used in this work acts as a pair of single-negative materials [18, 19]. In such a structure, magnetic polariton excitations [19–22] can be excited and sustained, since the system demonstrates a diamagnetic behaviour. The simulations of magnetic polariton resonant frequency in reflectivity as the function of geometrical size of the metacell of the structure depicted in Fig. 1(b) are presented in Fig. 2. Due to the conductive n-GaAs ground plane the samples are opaque in the terahertz region, and therefore the relation of $A = 1 - R$ holds, where A stands for absorptivity and R for reflectivity. Also, according to Kirchhoff's law, at the thermodynamic equilibrium the absorptivity equals the emissivity. Using the data presented in Fig. 2 it is straightforward to find what frequency corresponds to which geometrical side length of the square metacell and vice versa. Therefore, Fig. 2 could be used in order to find which spectral peak corresponds to which element of the metacell even for complex structures as depicted in Fig. 1(a).

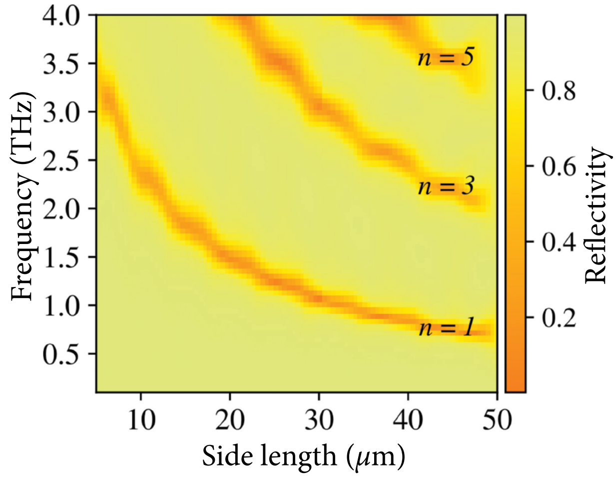

Fig. 2. The simulated dependence of magnetic polariton resonance frequency in reflectivity on the side length of the metacell in the n-GaAs/GaAs/Ti/Au structure used in this work. The 1st, 3rd and 5th harmonics of magnetic polaritons ($n = 1, 3, 5$) are present.

Simulations employing the rigorous coupled wave analysis (RCWA) method were performed for both structures of interest (Fig. 1(a)) and for two cross polarizations projecting the E-vector along (s-polarization) and across (p-polarization) the structures. The simulated spectra of the Trident emissivity are depicted in Fig. 3(a). The sharp main harmonic peaks of magnetic polaritons are visible in the spectra at 0.85 and 1.08 THz and the 3rd harmonic peaks at 2.53 and 2.95 THz for the p-polarized and s-polarized radiation, respectively. Also, in the case of p-polarization the peak at 3.8 THz appears, which might be related to the 5th harmonic of magnetic polariton.

The simulated emissivity spectra for the CG metasurface case are shown in Fig. 3(b). Here a strong single peak is present at 0.72 THz in the case of p-polarization, while a low-amplitude peak centered at 0.98 THz appears at s-polarization. These are the main harmonics of magnetic polaritons excited in the structure. At higher frequencies, spectral features at around 2.1 THz are observed for both polarizations representing the 3rd harmonic. Moreover, peaks at 3 THz (s-polarization) and 3.5 THz (p-polarization) are present. The frequencies of these resonances are too low to represent the 5th harmonics, therefore

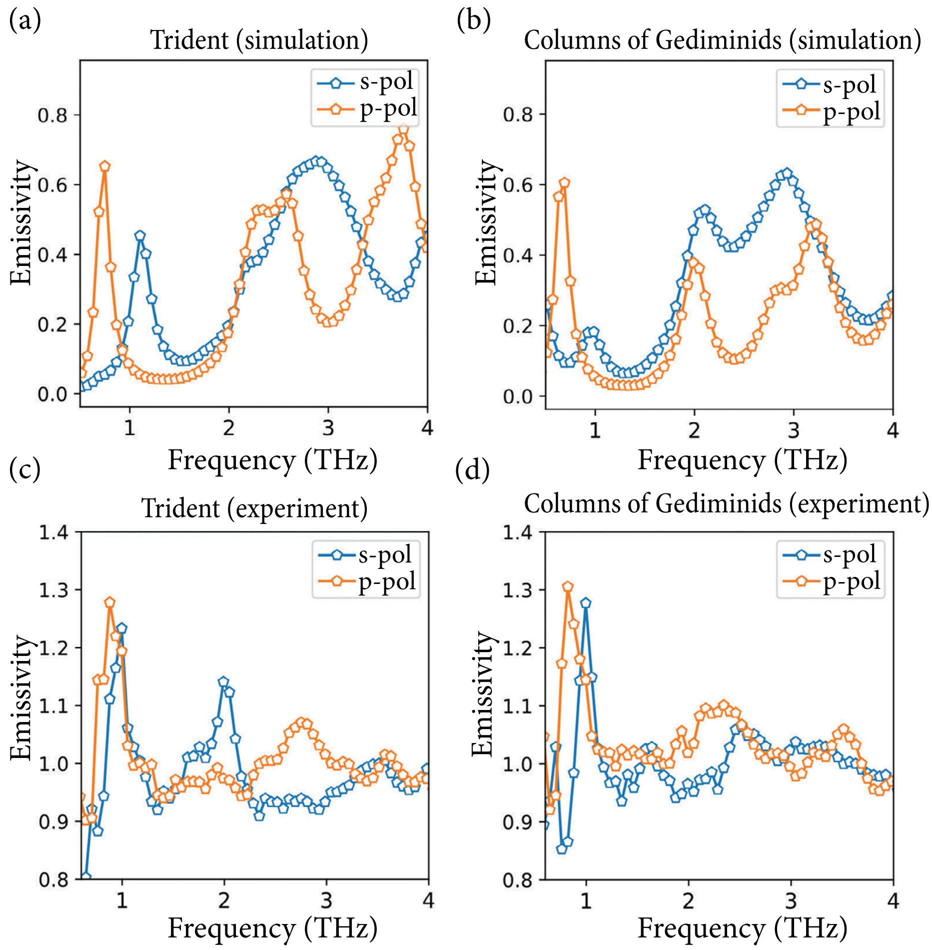

Fig. 3. The simulation (a, b) and experimentally measured (c, d) spectra of the Trident (Trizub) and the Columns of Gediminids, respectively for s- and p- polarizations.

their origin might be related to the excitation of magnetic polaritons in the other parts of the CG metasurface since it has a complex geometry.

The experimentally measured emissivity spectra are shown in Fig. 3(c, d) for the Trident and the Columns of Gediminids, respectively. In the case of Trident, the well distinguished peaks representing the 1st MP harmonics are observed at 0.80 THz (p-polarization) and 1.02 THz (s-polarization), showing, however, a much smaller separation in the resonant frequencies between cross-polarizations. Also, in the s-polarized spectrum the feature at 2.00 THz is present, which is much less than triple of the main harmonic frequency (1.02 THz) and also does not coincide with any spectral line represented in the simulations (Fig. 3(a)). As for the p-polarized spectrum the 3rd harmonic is visible at 2.78 THz. Both the main and the 3rd harmonics in this case are blue shifted as compared to the simulated results (Fig. 3(a)).

The experimental spectra of the Columns of Gediminids are dominated by the sharp 1st harmonic resonances for both polarizations. In the case of p-polarization, the resonance occurs at 0.80 THz and coincides well with the simulated data, the same coincidence is valid in the case of s-polarization, where the experimental resonance takes place at 1.00 THz (Fig. 3(d)). The higher frequency part of the spectrum in p-polarization also demonstrates two distinct peaks, with their positions blue shifted by about 300 GHz if compared to the simulated values. The broad spectral feature of the simulated s-polarization spectrum is also reflected in the experimental data in Fig. 3(d), however, of a much weaker amplitude and shifted by about 300 GHz. As can be seen, the frequency shift between the simulated and experimental values is the same for both polarizations. Since the frequencies of the broad structure do not appear to represent the 3rd harmonic of the frequency of sharp peaks observed at lower frequency, most probably higher and lower frequency resonances are excited in different parts of the metacell. Therefore, it would be useful to check which part of the metacell is responsible for which resonance by decomposing the metacell into its constituents. Since it would take a lot of effort to prepare a set of the samples containing only different parts of the metacell, further in this work, the decomposition of metacells and

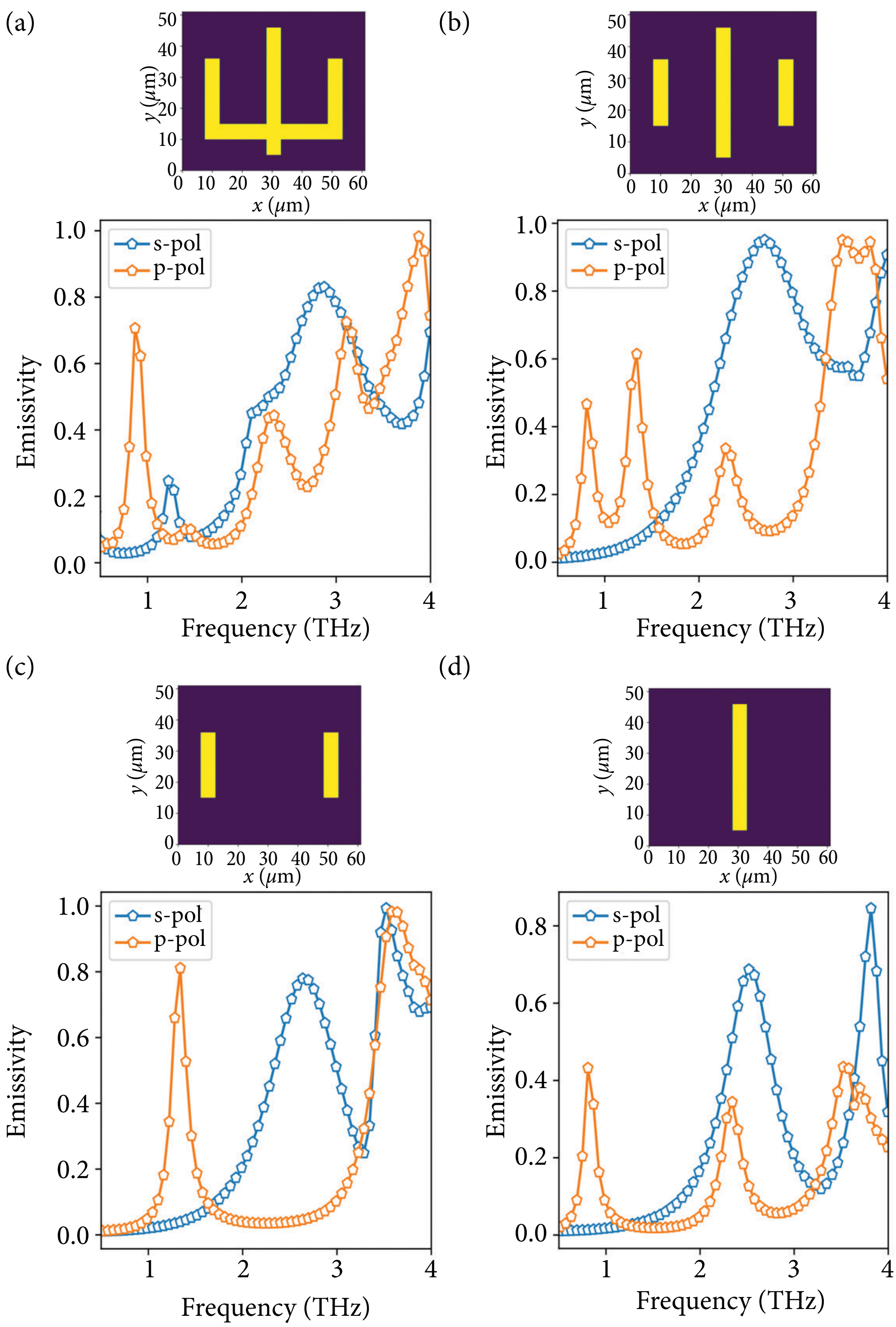

Fig. 4. The simulated emissivity spectra in the s- and p- polarizations of the separate parts constituting the Trident. The insets above each graph represent the form of the metacell. Here the light colour denotes the metal paths.

the optical response for each case were done only numerically.

Figure 4 represents the simulated spectra of four different parts constituting the Trident metacell. Part (a) of this figure demonstrates the spectra for the TR part omitting the top 'claws' on top of each lateral bar. Comparison with the spectra simulations for the whole TR structure (Fig. 3(a)) reveals the appearance of two new peaks in the p-polarization at 1.40 and 3.15 THz. When the horizontal bar is removed (Fig. 4(b)), the structure of the 1.40 THz peak grows in amplitude; however, the peak at 3.15 THz disappears. Further on, by removing the central bar in Fig. 4(c) the peaks at 0.85 and 2.45 THz are diminished in the p-polarization, and the peak at 3.72 THz appears in the s-polarization. Finally, when only the central vertical bar is considered (Fig. 4 (d)), the peaks at 0.85 and 2.45 THz reappear in the p-polarized spectrum. It can be concluded that the components due to the excitation of the main (0.85 THz) and the 3rd harmonic (2.45 THz) of magnetic polariton modes along the central vertical bar dominate the original p-polarized spectrum presented in Fig. 3(a). As for the s-polarized spectrum, the main component at 2.95 THz comes from the MPs excitation across the central and lateral bars. In the experimental spectra (Fig. 3(c)), p-polarization is dominated by the 1st and 3rd harmonics due to MPs along the central vertical bar, and s-polarization is dominated by the peak related to MPs along the horizontal bar. Interestingly in this case, no influence from the excitations along vertical bars is observed in the experiment, while they are very prominent in simulations.

Figure 5 represents the simulated spectra of four different parts constituting the metacell of the Columns of Gediminids. Part (a) of this figure demonstrates the spectra for the CG part omitting the central part of metallization. Here, the peaks at 0.70 and 2.12 THz for the p-polarization are present thus representing the 1st and 3rd harmonics of MPs excited along the lateral vertical bars, respectively. The peak in the s-polarization at 2.75 THz represents the magnetic polariton localized across the vertical bars, while the peak at 1.00 THz is for the MP resonance located along the bottom vertical bar. The peak in the p-polarized spectrum in Fig. 5(b) shifts to 0.75 THz, this is because by removing the horizontal bar the length of vertical bars was reduced by 5 μm and for MPs resonant frequencies blueshift with decreasing the length of metacell. Also, the 3rd and 5th harmonics can be seen. In the s-polarization, the resonance frequency does not change, since the width of metallic bars remains the same. When the central part of the CG metacell is considered (Fig. 5(c)), the peaks at 0.85 and 1.50 THz appear, while the one at 2.12 THz is maintained in the p-polarization. For the s-polarization, the peaks at 1.78 and 2.95 THz are present, the former one accounting for the MP excitation along the horizontal bar, and the latter one across the vertical bars shifted up in frequency. The shift from 2.75 to 2.95 THz likely comes from the non-trivial interaction between the magnetic fields excited below the vertical and horizontal bars in such a 'closely packed' structure. After the horizontal bar is removed, as shown in Fig. 5(d), the double spectral feature appears to be composed from components located at 1.5 and 1.75 THz, which are the fingerprints of the resonant behaviour below the central vertical bar and two lateral vertical bars, respectively. In the s-polarization, the single peak at 2.75 THz exists, most probably with the frequency detuned from the previously observed 2.95 THz back to one that is common for the bars of 5 μm width. Comparing these findings with the spectrum of the whole Columns of Gediminids metacell in Fig. 3(b), it can be deduced that the main influence comes from the lateral vertical bars in the p-polarization, since the spectral features accounting for the 1st, 3rd and 5th MPs harmonics along the structures can be seen. In the spectrum of s-polarization, the central structure response comes into play (peak at 2.95 THz), and peaks due to the excitations along the bottom horizontal bar (1.00 THz) and along the vertical bar of the central structure are manifest as well. In the experimental spectrum (Fig. 3(d)), however, the spectral fingerprints of the well-expressed 1st harmonic and the strongly diminished 3rd and 5th harmonics are observed in the p-polarization case. While for the s-polarization a surprisingly strong (compared to simulations) peak caused by the horizontal bar at 1.00 THz is seen together with small features coming from the resonances across the vertical bars. Also, the peak at 1.5 THz common to the central structure of GC design is present.

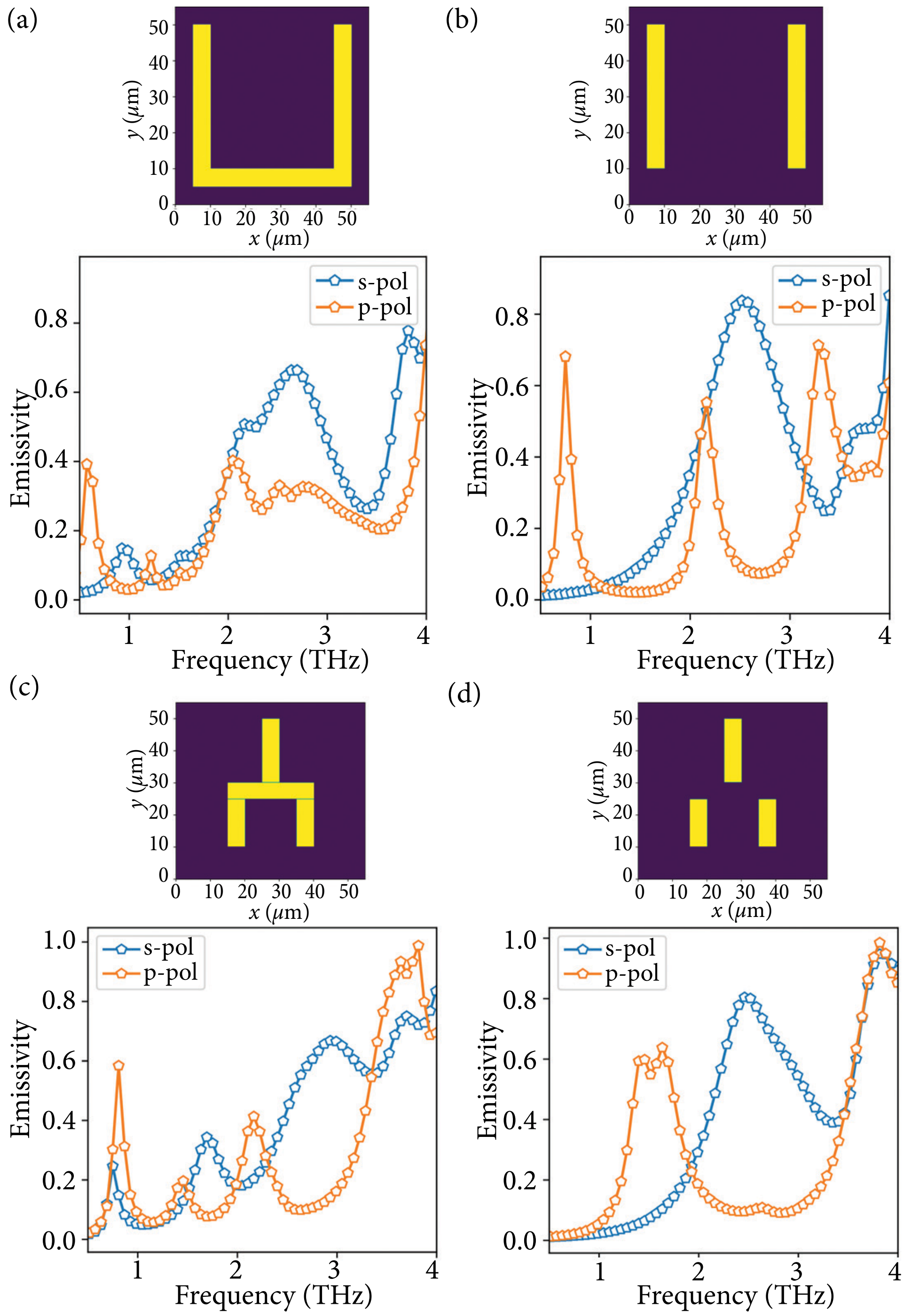

Fig. 5. The simulated emissivity spectra in the s- and p- polarizations of the separate parts constituting the Columns of Gediminids. The insets above each graph represent the form of the metacell. Here the light colour denotes the metal paths.

4. Conclusions

To sum up, the emission from the n-GaAs/GaAs devices equipped with the Ti/Au metasurfaces composed either from the Lithuanian Columns of Gediminids or the Ukrainian Trident was investigated in the THz range. It was revealed that the emission spectra of both metasurfaces have similarities in the frequencies close to 1 THz, where the resonant features due to the magnetic polariton excitations under the lateral vertical bars in the s-polarization and the resonant features due to the magnetic polaritons excited under the bottom vertical bars in the p-polarization. From the historical point of view, the theory suggesting that the Columns of Gediminids may have evolved from the Ukrainian Trident exists. The question of whether these symbols share a common origin or not is left to historians to investigate.

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TERAHERCŲ EMISIJOS SPEKTROSKOPIJA PAVIDALŲ PANAŠUMUI TIRTI: UKRAINOS IR LIETUVOS SIMBOLIŲ NAGRINĖJIMAS

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Santrauka

Šiame darbe nagrinėjama n-GaAs/GaAs struktūrų su Ti/Au metapaviršiais šiluminė emisija terahercinio dažnio srityje. Pasirinkta metapaviršių sudarančių metaatomų forma atspindi valstybinius simbolius, konkrečiai ukrainietiškąjį tridantį (*тризуб*, trizub) bei lietuviškuosius Gediminaičių stulpus. Eksperimentiniai tyrimai buvo atliekami naudojant tolimosios infraraudonosios srities Furjė spektroskopijos metodus, kai spinduliuotės šaltinis yra pats bandinys, pakaitintas iki 240 °C temperatūros. Siekiant paaiškinti stebėtų spektrinių ypatumų prigimtį, optiniai bandinių parametrai buvo sumodeliuoti naudojantis griežtosios susietųjų bangų analizės metodu. Sumodeliuotų spektrų dekonstravimas buvo atliktas modeliuojant atskirų metaatomus sudarančių struktūrų spektrus. Atlikta spektrinė analizė parodė, kad tyrinėti heraldiniai valstybių simboliai turi panašumų, o tai atsispindi ir istoriniame kontekste.