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Communication

Directivity Control of Terahertz Radiation from Single-Color Filament Plasma with Polypropylene Pipe

Daria Mokrousova [1,2], Leonid Seleznev [2,*], Dmitrii Pushkarev [2], Georgy Rizaev [2], Maximilian Levus [1], Andrey Koributi [2] and Yakov Grudtsyn [2]

1 Faculty of Physics, Lomonosov Moscow State University, 119991 Moscow, Russia
2 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, 119991 Moscow, Russia
* Correspondence: seleznev@lebedev.ru

Abstract: Two-dimensional angular distribution of terahertz emission from single-color filamentation of laser pulses is experimentally studied. The use of a polypropylene pipe makes it possible to transform the angular pattern of terahertz radiation from the original hollow-cone one to a more preferable unimodal structure within the terahertz frequency range. It has been shown that propagation in a dielectric pipe can significantly (up to several orders of magnitude) increase the terahertz radiation amplitude at a required distance. We have also experimentally demonstrated that bending the pipe allows us to control the direction of the terahertz radiation propagation.

Keywords: terahertz radiation; filamentation; non-linear optics

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1. Introduction

The variety of applications [1,2], together with the complexity of its generation, has made terahertz frequency range radiation the subject of numerous studies. One of the terahertz radiation sources is air plasma formed by ultrashort high-power laser pulses [3–5]. The simplest method used to generate terahertz radiation is single-color filamentation of laser pulses [6]. The plasma of a single-color filament emits radiation into a hollow cone [7], wherein the spectral composition depends on propagation angle [8]. Such a spectral-angular pattern of terahertz emission significantly complicates its practical applications; therefore, the goal is to find a way to transform a wide hollow-cone distribution to a unimodal one. To solve this problem, it was proposed to use the interference of terahertz radiation from an ordered array of filaments [9] or several filaments with a time delay converging at some specific angle [10,11]; however, both methods are technically complicated. In addition, it is often necessary to deliver terahertz radiation from the source to the object under study. One of the methods for such delivery can be the use of a dielectric waveguide [12], or even a dielectric pipe with a large core diameter but thin walls [13]. In such pipes, the absorption coefficient can be as small as 10^{-2}–10^{-3} cm^{-1} [12,13]. However, the angular distribution of terahertz radiation can change during propagation through the waveguides or pipes. It should be mentioned that in the pipes presented in [13], the interference inside the walls is used as a mechanism to provide guidance. This mechanism does not work in case of a short terahertz pulse, for which the propagation time in the walls is much longer than the pulse duration, so initial and reflected pulses do not overlap in a time domain. Therefore, the aim of our work is to study the possibility of using a thick-wall dielectric pipe to deliver a short terahertz emission pulse from single-color filament plasma and change its angular distribution.

2. Materials and Methods

We conducted our experiments with the radiation of a Ti:Sapphire laser system, (Avesta Ltd., Moscow, Russia) generating pulses with a central wavelength of 930 nm, a duration of 150 fs, and a repetition rate of 10 Hz. The beam diameter was 1 cm at the $1/e^2$ level. Terahertz radiation emitted by the filament plasma was detected by a superconducting hot-electron NbN bolometer (Scontel, Moscow, Russia). Since terahertz radiation of different frequencies propagates at different angles, and the bolometer detects radiation in a wide frequency range (0.1–6 THz), we put the narrow-band terahertz filters in the front of the bolometer [14]. A 90 cm-long polypropylene pipe with an inner diameter of 13 mm and a wall thickness of 3.4 mm was used in the experiment. The pipe geometry does not provide the waveguide propagation neither in its traditional sense, (when the refractive index of the waveguide core is higher than that of the cladding), nor in the sense of the interference mechanism proposed in [13]. Figure 1 shows the scheme for recording the two-dimensional angular distribution of terahertz radiation after the pipe. The polypropylene pipe was parallel to the table. The geometric focus of a spherical mirror or a lens was located in the center of the pipe's inlet. The other pipe end coincided with the rotation axis of the bolometer. The input pipe end, through which the terahertz beam entered the tube, was rigidly fixed by mount 1 (Figure 1a). Mount 2 fixed the pipe bending point, and the output pipe end was moved vertically by mount 3, which changed the vertical angle ϕ_{ver} of the direction to the bolometer window relative to the terahertz radiation propagation axis. At a fixed vertical angle, the horizontal angular distribution was measured by rotating the bolometer in the plane of the table (Figure 1b). The geometry of the scheme provided an angular resolution of 1.7 degrees. Since the angles at which the signals exist are small (less than 4°), the curvature of the pipe did not change the distribution of the terahertz radiation exiting it. This was also checked experimentally by slight bending of the tube in the horizontal plane. The observed distribution remained the same but was rotated at a corresponding angle, which proved the applicability of our measurement method. The referenced two-dimensional angular distributions without the pipe were also measured. In this case, the lens focus was placed on the rotation axis of the bolometer and the experiment was carried out according to the technique described in [15].

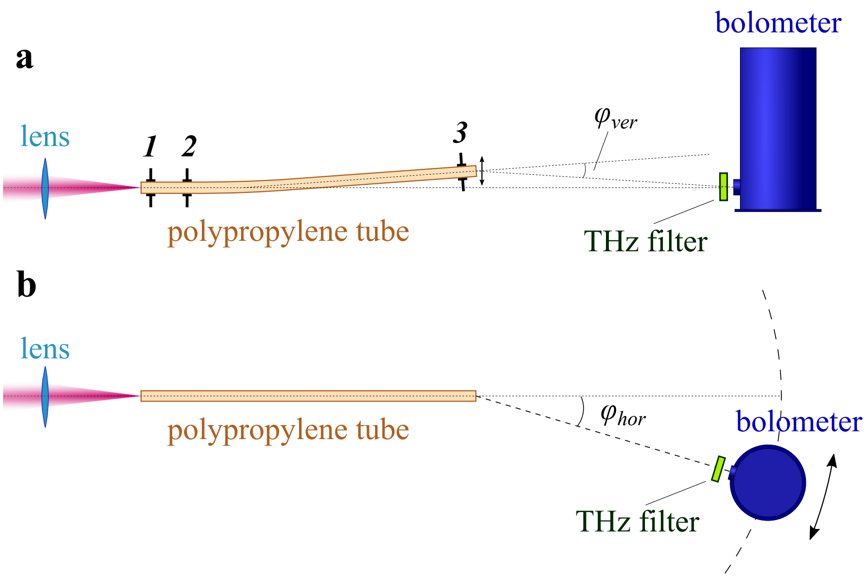

Figure 1. Scheme of the experiment: (**a**) side view; (**b**) view from above. 1–3–mounts fixing the pipe.

3. Results and Discussion

First, before installing the pipe, we studied the angular distribution of terahertz radiation generated by a single-color filament plasma. Laser pulses with energy of 3 mJ were focused by the spherical mirror with a focal length of 1 m. In this case, we have a single-filament mode of laser propagation. Figure 2 shows the angular pattern of terahertz radiation with frequencies of 0.5 (a) and 1 THz (b). At higher frequencies (namely, 3 THz) the signal-to-noise ratio was close to unity. The measured angular distributions (Figure 2) had a ring-shaped structure. As described in [8], higher terahertz frequencies propagated into the smaller angles. Then, we measured the patterns in the presence of the pipe. In this case, the angular distribution of terahertz radiation had a unimodal structure (Figure 2c,d), i.e., instead of the original hollow cone, a narrowly directed terahertz beam was observed. If the pipe was removed in this experimental geometry, no signals were observed on the bolometer. Further, we made sure that the obtained patterns persisted in the case of tighter focusing, at which the terahertz radiation propagates at larger angles, so the expected difference between the angular distributions with and without the pipe was even more significant.

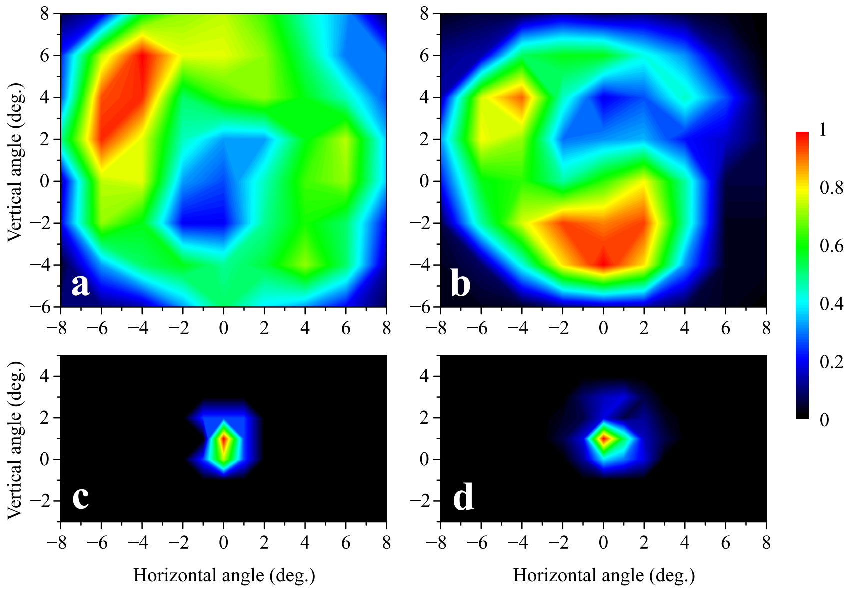

Figure 2. Normalized angular distributions of the radiation with frequencies of 0.5 THz (**a**,**c**) and 1 THz (**b**,**d**), without (**a**,**b**) and with (**c**,**d**) the polypropylene pipe. Focal length is 1 m, laser pulse energy is 3 mJ.

For that purpose, we focused our laser beam with pulse energy of about 10 mJ for the lens with the focal length of 20 cm. In this case, we had several plasma channels (multi-filament mode). Figure 3a shows the angular distributions of terahertz radiation in the horizontal plane at frequencies of 0.3, 0.5, and 1 THz. At all frequencies, we observed a two-maxima structure with a minimum on the axis, which likely indicates that terahertz radiation propagates in a hollow cone. The distributions of terahertz radiation obtained for the same frequencies after the pipe are shown in Figure 3b–d. As in the milder focusing case, the terahertz radiation after the pipe had a unimodal distribution at all considered frequencies. If the initial cones had opening angles of more than 15° (Figure 3a), then after the pipe, the width of the angular distribution of terahertz radiation at the ½ level was about 4° (Figure 3b–d). Therefore, despite the significant difference between the initial angular patterns of terahertz emission under different focusing conditions, the unimodal structures formed by the pipe were qualitatively the same.

For potential applications, it is important not only to obtain narrow-angle emission pattern, but also to have an opportunity to control its direction. To test the direction control, we carried out an experiment, the scheme of which is shown in Figure 4a. In this experiment, we used a polypropylene pipe similar to the previously used one, but smoothly bent by the angle of 35° (radius of curvative ∼25 cm). The measurements of the angular distribution of terahertz radiation were carried out according to the method described above; the bolometer was rotated around an axis passing through the output pipe end (Figure 4a). The angular distribution of terahertz radiation with frequencies of 0.5 and 1 THz is shown in Figure 4b,c. As in the experiment with the straight pipe, the main maximum was located on the axis, but in this case, two additional maxima appeared in the horizontal (i.e., bending) plane. The amplitude of one of them was comparable to the main maximum, and the amplitude of the second was much lower. Apparently, the appearance of the additional maxima may be due to the reflection anisotropy in the bending region.

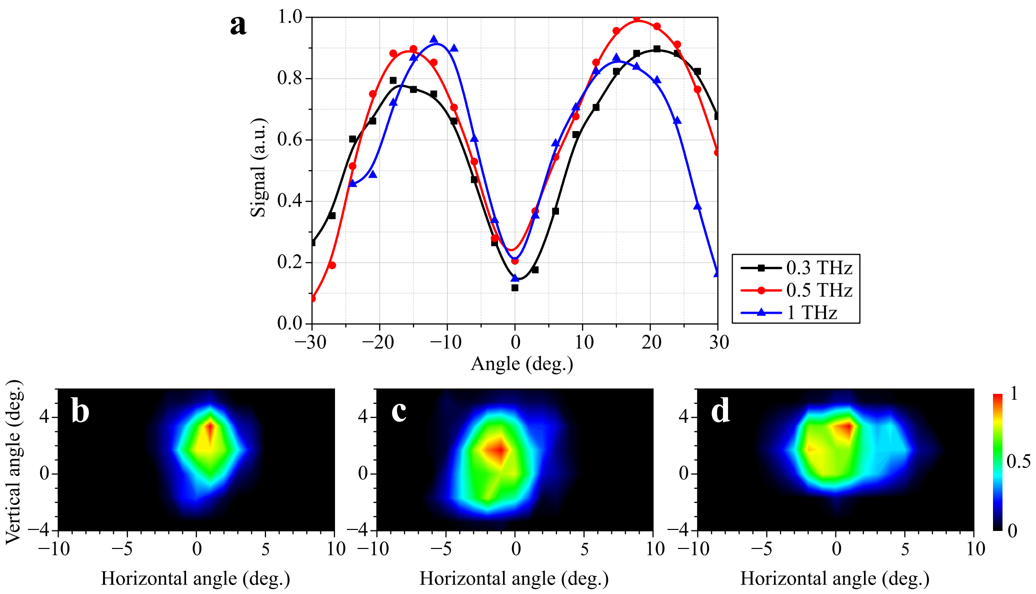

Figure 3. Normalized angular distribution of terahertz radiation without the pipe (**a**) and with the use of the polypropylene pipe for frequencies: 0.3 THz (**b**), 0.5 THz (**c**) and 1 THz (**d**). The focal length is 20 cm, laser pulse energy is 10 mJ.

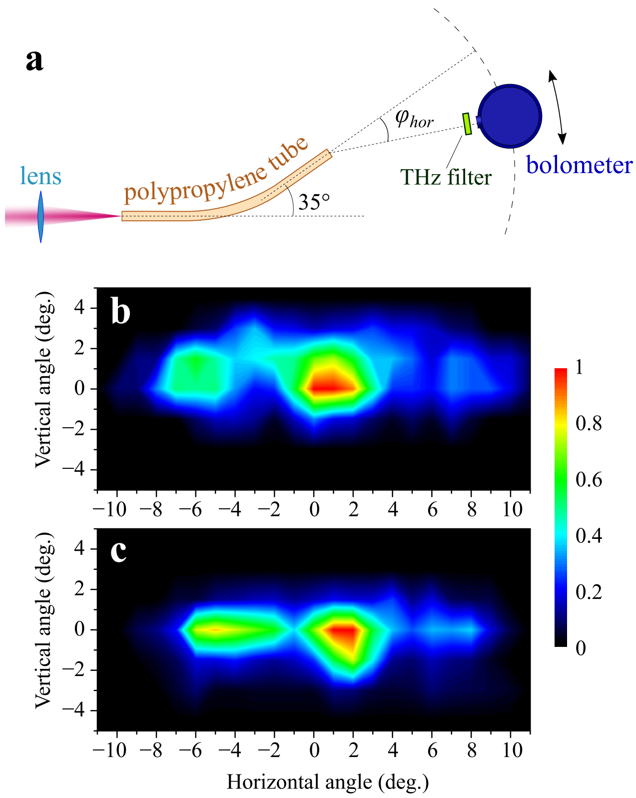

Figure 4. Scheme of the experiment with the bent pipe (**a**). Angular distribution of the radiation with frequencies of 0.5 THz (**b**) and 1 THz (**c**) passed through the bent pipe.

Since polypropylene, from which the pipe is made, has low absorption in the terahertz frequency range, and the maximum wavelength of terahertz radiation in this experiment

(600 µm for a frequency of 0.5 THz) is significantly less than the pipe wall thickness (3.4 mm), there is a possibility of propagation of terahertz radiation inside the walls. In order to establish where the radiation propagates, we installed a metal screen at the pipe input in such a way that it blocked the central hole, but did not block the walls. In this case, the observed terahertz signals completely disappeared. If, however, we installed a large metal diaphragm, leaving only the central hole open, then the measured terahertz signals practically did not change. We verified this for both the input and the output ends of the pipe. Similar results were obtained for the straight pipe. Consequently, terahertz radiation propagated inside the central opening, and not the walls of the polypropylene pipe.

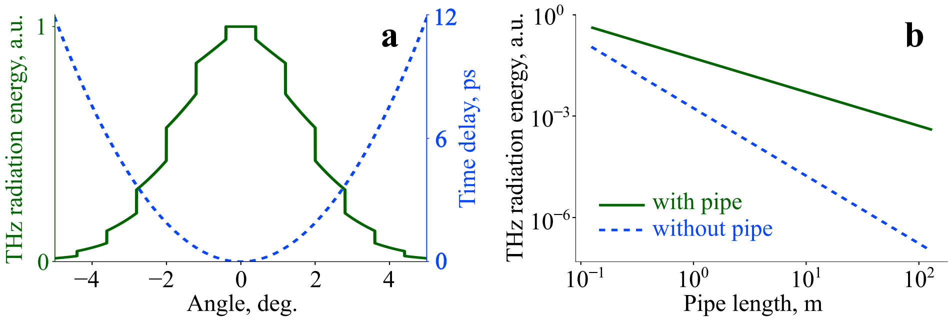

Figure 5. Terahertz radiation angular distribution at the pipe output (green solid line) and delay of the terahertz pulse depending on the propagation angle (blue dashed line) (**a**). Energy of terahertz radiation contained in the aperture corresponding to the pipe diameter depending on the distance for free propagation and propagation in the pipe (**b**).

Since the terahertz radiation propagated in the pipe's hollow part, we simulated it using the following model. The reflection coefficient of terahertz radiation from the pipe walls was determined by the Fresnel equations, depending on the incidence angle and the refractive index of the pipe material. The refractive index of polypropylene in a wide range of terahertz frequencies was 1.5 [16,17]. We took a model source of terahertz radiation emitting a spherical wave that propagated in a cone with an opening angle of 10 degrees. The normalized angular distribution of terahertz radiation at the output end of the 0.9 m long pipe, obtained as a result of the calculations, is shown in Figure 5a. In the paraxial region, the transmission was equal to one, which corresponds to free propagation from the source to the output aperture of the pipe. The propagation of terahertz radiation at large angles led to its reflections from the pipe walls, which corresponds to sharp energy drops on the graph. At angles of about 2 degrees, the energy density of terahertz radiation became lower than $1/e$ level of the amplitude on the axis. In addition, with an increase in the angle, the length of the path from the source to the pipe output aperture increased, resulting in an increase in the delay of the terahertz pulse relative to its propagation along the axis (Figure 5a). It should be noted that a significant part of the terahertz pulse energy was contained in angles of less than 2 degrees, which corresponds to a delay of about 3 ps. This is comparable to the initial terahertz pulse duration. Increasing the dielectric pipe length did not lead to a significant growth of the delay, since the effective propagation angles of terahertz radiation simultaneously decreased. During free propagation, only a small part of the terahertz radiation propagated into the angles determined by the output aperture and the length of the pipe. In this case, a significant part of the radiation was contained in the wings of the distribution shown in Figure 5a. From this point of view, it is interesting to evaluate the dependence of the efficiency of terahertz radiation transfer on the dielectric pipe length. The dashed line in Figure 5b shows the free propagation of terahertz radiation into the angle corresponding to the pipe output aperture at a given distance, and the solid line shows the efficiency of terahertz radiation transmission through the pipe depending on its length. Thus, the use of a long dielectric pipe (about 10^2 m) makes it possible to increase the transmission efficiency of terahertz radiation by more than three orders of magnitude.

4. Conclusions

Thus, in this work, we have experimentally demonstrated that with a dielectric pipe, one can change the angular distribution of terahertz emission during single-color filamentation. In the experiments, the initial cone-shaped terahertz radiation pattern was transformed into a narrower unimodal structure. Moreover, changes in the opening angle of the incident cone-shaped angular distribution did not qualitatively affect the resulting unimodal pattern after the beam. We also demonstrated that it is possible to control the propagation direction of the resulting terahertz beam by bending the pipe. It has been demonstrated that propagation in a dielectric pipe can significantly (up to several orders of magnitude) increase the terahertz radiation amplitude at the required distance. Such a narrow-directed terahertz angular pattern can be favorable for any possible applications [1,2] of filament-generated terahertz radiation.

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Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Zhang, X.C.; Xu, J. *Introduction to THz Wave Photonics*; Springer: New York, NY, USA, 2010; Volume 29, p. 246.
2. Zhang, Y.; Li, K.; Zhao, H. Intense terahertz radiation: Generation and application. *Front. Optoelectron.* **2021**, *14*, 4–36.
3. Hamster, H.; Sullivan, A.; Gordon, S.; White, W.; Falcone, R. Subpicosecond, electromagnetic pulses from intense laser-plasma interaction. *Phys. Rev. Lett.* **1993**, *71*, 2725.
4. Cook, D.; Hochstrasser, R. Intense terahertz pulses by four-wave rectification in air. *Opt. Lett.* **2000**, *25*, 1210–1212.
5. Löffler, T.; Jacob, F.; Roskos, H. Generation of terahertz pulses by photoionization of electrically biased air. *Appl. Phys. Lett.* **2000**, *77*, 453–455.
6. Sun, W.; Wang, X.; Zhang, Y. Terahertz generation from laser-induced plasma. *Opto-Electron. Sci.* **2022**, *1*, 220003.
7. D'Amico, C.; Houard, A.; Franco, M.; Prade, B.; Mysyrowicz, A.; Couairon, A.; Tikhonchuk, V.T. Conical Forward THz Emission from Femtosecond-Laser-Beam Filamentation in Air. *Phys. Rev. Lett.* **2007**, *98*, 235002.
8. Rizaev, G.E.; Seleznev, L.V.; Mokrousova, D.V.; Pushkarev, D.V.; Ionin, A.A. Terahertz emission pattern from a single-color filament plasma. *Opt. Lett.* **2022**, *47*, 5917–5920.
9. Panov, N.; Andreeva, V.; Kosareva, O.; Shkurinov, A.; Makarov, V.; Bergé, L.; Chin, S. Directionality of terahertz radiation emitted from an array of femtosecond filaments in gases. *Laser Phys. Lett.* **2014**, *11*, 125401.
10. Mitryukovskiy, S.I.; Liu, Y.; Prade, B.; Houard, A.; Mysyrowicz, A. Coherent synthesis of terahertz radiation from femtosecond laser filaments in air. *Appl. Phys. Lett.* **2013**, *102*, 221107.
11. Mitryukovskiy, S.I.; Liu, Y.; Prade, B.; Houard, A.; Mysyriwicz, A. Coherent interaction between the terahertz radiation emitted by filaments in air. *Laser Phys. Lett.* **2014**, *24*, 094009.
12. Chen, D.; Chen, H. A novel low-loss Terahertz waveguide: Polymer tube. *Opt. Express* **2010**, *18*, 3762–3767.
13. Lai, C.H.; Hsueh, Y.C.; Chen, H.W.; Huang, Y.J.; Chang, H.C.; Sun, C.K. Low-index terahertz pipe waveguides. *Opt. Lett.* **2009**, *34*, 3457–3459.
14. Rizaev, G.E.; Pushkarev, D.V.; Koributt, A.V.; Grudtsyn, Y.V.; Mokrousova, D.V.; Savinov, S.A.; Mityagin, Y.A.; Seleznev, L.V.; Kosareva, O.G.; Ionin, A.A. Transformation of the frequency-angular spectrum of THz emissions produced by a single-color laser filament under an external electrostatic field of various strength. *Laser Phys. Lett.* **2021**, *18*, 115401.
15. Rizaev, G.E.; Mokrousova, D.V.; Pushkarev, D.V.; Shipilo, D.E.; Nikolaeva, I.A.; Panov, N.A.; Seleznev, L.V.; Kosareva, O.G.; Ionin, A.A. Breaking of the Axial Symmetry of Terahertz Radiation from Single-Color Filament Plasma. *JETP Lett.* **2022**, *115*, 657–659.

16. Jin, Y.S.; Kim, G.J.; Jeon, S.G. Terahertz dielectric properties of polymers. *J. Korean Phys. Soc.* **2006**, *49*, 513.
17. Fedulova, E.; Nazarov, M.M.; Angeluts, A.; Kitai, M.; Sokolov, V.; Shkurinov, A. Studying of dielectric properties of polymers in the terahertz frequency range. In *Saratov Fall Meeting 2011: Optical Technologies in Biophysics and Medicine XIII*; SPIE: Saratov, Russia, 2012; Volume 8337, pp. 144–152.