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Image Transmission with the Subwavelength Resolution in Microwave, Terahertz, and Optical Frequency Bands

P. A. Belov[a,d], C. R. Simovski[a], P. Ikonen[b], M. G. Silveirinha[c], and Y. Hao[d]

[a] *St. Petersburg State University of Information Technologies, Mechanics, and Optics, Sablinskaya ul. 14, St. Petersburg, 197014 Russia*

e-mail: belov@phoi.ifmo.ru

[b] *Electromagnetics Laboratory, Helsinki University of Technology, Espoo, Finland*

[c] *University of Coimbra, Coimbra, Portugal*

[d] *Queen Mary University of London, London, United Kingdom*

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Abstract—An image transmission principle related to the transformation of the spatial spectrum of a source into modes propagating in a metamaterial with a flat isofrequency contour is proposed. This principle makes it possible to obtain a resolution much smaller than the wavelength. The proposed principle is implemented in the microwave, terahertz, and optical frequency bands with the use of a medium consisting of parallel metal wires. It is shown that the subwavelength transmission of images can be achieved in the visible optical band via the use of a periodic structure consisting of successive metal and dielectric layers. The resolution, operation bandwidth, and sensitivity to losses in component materials are estimated for all the proposed systems. The applicability of such structures in medicine, in near-field microscopy, and as components of optical data storages with increased capacity is considered.

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INTRODUCTION

The resolution of standard image transmission and processing devices is restricted by the so-called diffraction limit. The image details spaced by a half-wavelength distance cannot be recognized. This restriction arises only from the use of the propagating waves in image transmission and processing devices of the lens type. Information on subwavelength details is stored in evanescent waves of the spatial spectrum, which are concentrated in the immediate neighborhood of a source. At an insignificant distance from the source, this information disappears and cannot be processed by ordinary lens systems.

A possible way to overcome the diffraction limit via the use of artificial media with exotic electromagnetic properties, namely, media with both negative permittivity and permeability [1], was described in [2]. British scientist J. Pendry suggested the concept of a superlens capable of transmitting subwavelength details of an image through significant distances (namely, of the order of the wavelength) [2]. He showed that a layer of a material with both negative permittivity and permeability can create images with perfect resolution. Unfortunately, it has been shown [3] that an experimental implementation of lenses with perfect resolution is impossible because the smallest losses in a metamaterial lead to significant degradation of the lens resolution.

Note that this hypothetical composite (such media do not exist in nature) is called the Veselago medium in honor of the Soviet scientist who first proposed to consider a medium with such electromagnetic properties and who studied some of the physical effects inherent in this medium [1]. Reassessment of the classical concept of the diffraction limit made in [2] stimulated rapid development of a new field of physics, which is now referred to as the physics of metamaterials.

Metamaterials are artificial media with electromagnetic properties that cannot be observed in natural materials. For example, in such a metamaterial as the Veselago medium, evanescent (decaying) waves grow when they propagate from a source of light to the observation point, rather than decay, as in ordinary media (Fig. 1).

The theory of Pendry's superlens is based on the above property of the Veselago medium and certain other properties. A perfect image of Pendry's superlens is achieved (theoretically) through the use of such an exotic property of the Veselago medium as backward waves (their wave vectors are strictly opposite to the radiation vector in the Veselago medium) and the effect of negative refraction related to this property. The far field of a source is focused in the image plane due to the negative diffraction at the boundaries of a medium layer. The near field, which contains information on subwavelength details, is recovered in the image plane via amplification of evanescent spatial harmonics in the

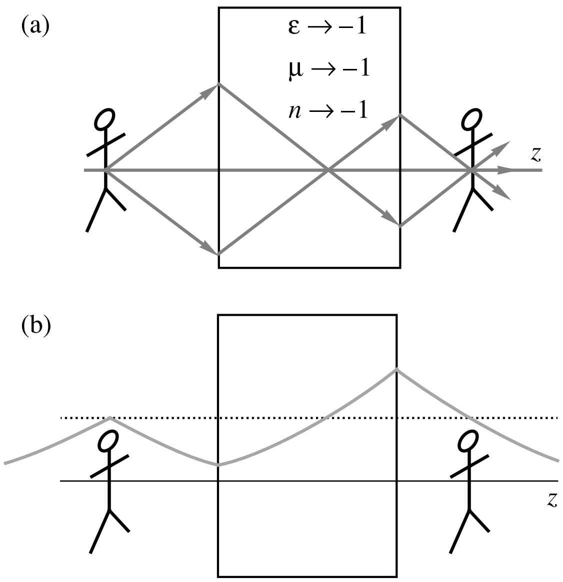

Fig. 1. Illustration of image transmission with superresolution [2] with the help of a superlens formed by the Veselago medium [1]: (a) focusing of the propagating spatial harmonics using the negative refraction effect and (b) amplification of the evanescent spatial harmonics.

medium. In free space or inside of a dielectric matrix, this information is lost at a certain distance from the source because evanescent spatial harmonics (carriers of subwavelength information) decay.

Amplification of evanescent waves has nothing in common with the concept of an active medium. The Veselago medium is passive. Amplification of evanescent harmonics propagating from a source to the observation point is one of the effects of spatial filtering, namely, redistribution of the reactive energy (usually concentrated in the neighborhood of a light source) from the near-field zone into the image region situated at a wavelength distance from it. In the absence of absorption of light in the medium, this process does not give rise to energy transfer and, consequently, does not violate the energy conservation law. In the presence of weak absorption, the conservation laws likewise are not violated. In this case, a layer of the Veselago medium serves as a device that matches the light source with the image formation region. In other words, the reactive energy concentrated in the near field is transformed into additional radiation inside of the absorbing Veselago medium. This radiation is transformed into the quasistatic field in the image region [4].

Although a superlens is of great importance for optical applications, materials with Veselago-medium properties, which have been created in recent years, can operate only at microwave frequencies [5]. Such media are difficult to implement in the infrared and optical bands, because it is not easy to obtain magnetic properties at these frequencies [6, 7]. All the natural materials and all the curriers of available composites do not exhibit magnetic behavior at these sufficiently high frequencies. Furthermore, significant losses inherent in materials with resonant inclusions do not allow application of the Veselago medium for imaging with a necessary superresolution, even if such a structure is created at these frequencies [3].

It is possible however to overcome the diffraction limit without using the Veselago medium and, furthermore, there is no need to create magnetic properties in the optical band therefore. Superlenses consisting of materials with a negative permittivity (silver, gold, and copper) are capable of transmitting images with a superresolution. This concept was suggested by Pendry as well [2]. Experimental results [8, 9] confirm its validity. However, application of such lenses is restricted because these devices can operate only on *p* (transverse magnetic (TM)) polarization and their thickness must be less than half of the wavelength.

Experiments [8, 9] have confirmed that it is possible to transmit optical images with the $\lambda/10$ resolution over a distance of approximately a quarter of the wavelength of light using the silver layers. However, in this case, an insufficiently high level of resolution is achieved because of the losses in silver. The resolution can be improved several times via the replacement of a single silver layer with a multilayer structure consisting of successive silver and dielectric layers with a thickness of the order of 10–20 nm [10, 11] or through the use of optically active composites [12]. However, in these structures, it is theoretically impossible to implement transmission of subwavelength details over a distance exceeding the wavelength of light. To accomplish the amplification of evanescent spatial waves, certain relationships between the thicknesses of silver and dielectric layers must be fulfilled; these relationships are very unfavorable for light transmission through the structure. When the total thickness of the structure is sufficiently small (less than half the wavelength of light in the dielectric material), it is theoretically impossible to eliminate reflection of a significant portion of the spatial radiation spectrum from the front surface of such a metamaterial. At present, there is no an acceptable way to eliminate the reflections when the thickness of Pendry's metal–dielectric superlens exceeds $\lambda/2$.

An interesting alternative to the Veselago media is use of photonic crystals that have a strong spatial dispersion in the optical range [13, 14]. In 2000, Japanese scientist Notomi described the effect of negative refraction at the boundary between free space and the photonic crystal, a phenomenon that occurs at frequencies close to the band-gap edges [15]. The possibility of subwavelength imaging by means of the planar layers of photonic crystals with transparent inclusions has been demonstrated both theoretically [16–19] and experimentally [20, 21].

Under certain conditions, amplitudes of the evanescent harmonics of the certain polarization excited in photonic crystals increase with distance from a source, this effect is similar to that observed in metal layers and, presumably, in the Veselago medium. Unfortunately, the resolution of such superlenses is limited by the spacing of the photonic crystal's lattice. This fundamental restriction has been stated and proved in [22]. As a result, it is practically impossible to obtain a subwavelength resolution (less than $\lambda/4$) in photonic crystals. Indeed, the effective wavelength in photonic crystals is λ/n (where n is the effective refractive index of the crystal). This value is comparable to the lattice spacing. Hence, a sufficiently large refractive index cannot be obtained, because optically transparent materials with a large contrast of the refractive index do not exist in nature. To achieve a resolution at a level of one-tenth of the wavelength, it is necessary to have a refractive index of the inclusions of a photonic crystal of the order of 10 if the inclusions are located in free space. In fact, inclusions are embedded in a dielectric matrix. Hence, a much larger refractive index of the inclusion material is required.

In the nearest future, the only way promising the possibility of transmitting the subwavelength details with a spatial resolution of $\lambda/10$ or better (in the visible optical band or in the infrared band) over distances greater than the wavelength of the light is to use the image canalization principle [23]. This method is based on the transformation of evanescent spatial harmonics into propagating modes of a certain metamaterial, rather than their amplification. Such transformation prohibits subwavelength information carried by evanescent harmonics from disappearance due to spatial attenuation of the waves. Being transformed into propagating modes, information about subwavelength details can be transmitted, in fact, over any necessary distance [23]. Thus, it is possible to implement an "optical telegraph" by means of using a metamaterial capable of transmitting images with a superresolution. Along with a cardinally different mechanism of image transmission, a key distinctive feature of canalization as compared to the principle of operation of the superlens proposed in [2] is insensitivity to the losses in the metamaterial. As a result, implementation of this method becomes substantially more attractive for applications.

The image canalization principle is a new and original solution that makes it possible to overcome the diffraction limit on the resolution of lens-based imaging devices. This method was developed in 2004 [23] and elaborated in subsequent research works [24–30], where metamaterials capable of implementing the image canalization regime in microwave, terahertz, infrared, and optical frequency bands were proposed and the potentialities of such materials to ensure image transmission with a subwavelength resolution over significant distances were demonstrated. Such metamaterials can be used in miniaturization of various optical and microwave devices, in medicine, and in near-field microscopy. The developed metamaterials make it possible to overcome the diffraction limit on the resolution of optical systems, which has remained unavoidable for a long time.

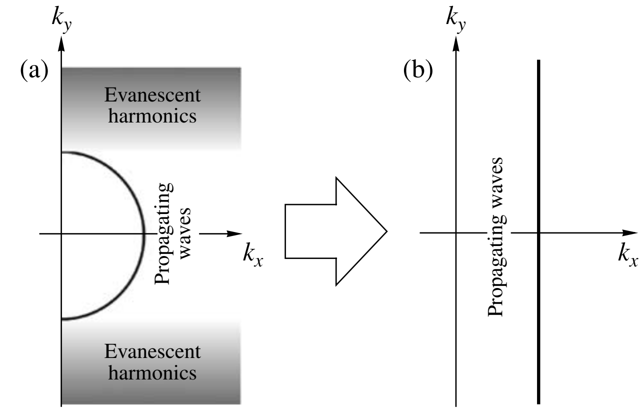

Fig. 2. Illustration of the image canalization principle: (a) isofrequency curve for free space (with marked regions of propagating and evanescent spatial harmonics) and (b) the isofrequency characteristic of a metamaterial that is required for the implementation of the canalization principle. (Evanescent spatial harmonics are absent.)

As the most important application of such materials, it suffices to mention that superresolution lenses can be used for increasing the capacity of optical storages (digital video discs (DVDs)) by decreasing their recording regions, which are now restricted by the diffraction limit. The obtained results are essential for the development of superresolution image transmission systems and can be considered an important achievement in the physics of metamaterials. In the authors' opinion, this progress must divert the researchers' attention from the attempts to create the Veselago medium to the development of other metamaterials whose electromagnetic properties are no less interesting and important.

1. FORMULATION OF THE IMAGE CANALIZATION PRINCIPLE

In their studies of negative refraction and image transmission with the use of photonic crystals, some scientists have revealed that, in certain cases, the physical mechanism of image transmission does not involve the effect of negative refraction. In photonic crystals, this effect is observed in the case of excitation of forward waves existing in the so-called first transmission zone [16, 19, 22] and in the case of backward waves corresponding to the second transmission zone [17, 18]. Many authors noted [23, 31–34] that, at the frequencies corresponding to the first transmission zone, image transmission sometimes occurs in the absence of negative refraction and without amplification of evanescent spatial harmonics. In [23],

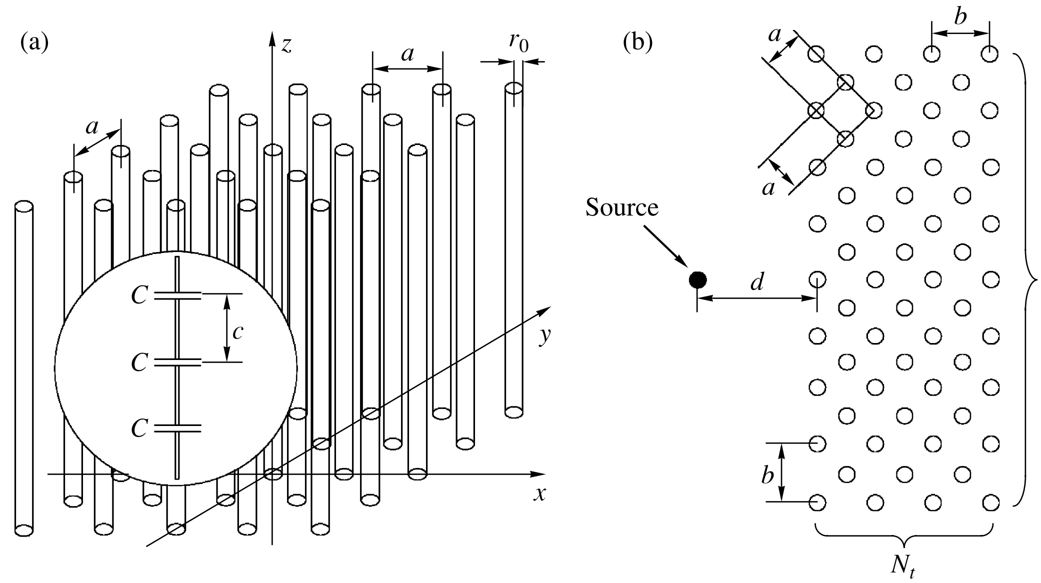

Fig. 3. (a) Medium consisting of wires with periodic capacitive loads [35] and (b) a layer of the wire medium used in [23] as a superlens. The structure parameters are as follows: $a = 10$ mm, $r_0 = 0.058a$, $c = 0.55a$, $C = 2$ pF, $N_l = 14$, $N_t = 21$, and $d = b = \sqrt{2}\,a$. The operating frequency is 2.2 GHz; this value corresponds to the wave number $k = 0.46/a$.

such a regime was called image canalization. For the first time, it was shown that a photonic crystal in this regime is a very specific metamaterial: It does not support evanescent waves (Fig. 2).

In the canalization regime, a metamaterial layer transmits an image from one surface of the layer to the other, i.e., operates as a waveguiding structure, unlike an ordinary lens, which forms a focal spot of radiation. This regime can be implemented only if a metamaterial has a flat isofrequency surface (see Fig. 2b) and the material thickness satisfies the Fabry–Perot resonance condition (equals an integer number of half-wavelengths) [23]. When the isofrequency characteristic is flat, all spatial harmonics created by a source (including evanescent harmonics) and refracted into the layer are transformed into propagating modes of the metamaterial. This feature allows transmission of subwavelength details over a significant distance. The propagating modes of a metamaterial transport an image from the layer's front surface to the back surface as if each point of the front surface is connected with the opposite point of the back surface via a waveguide.

The unavoidable reflection losses arising from the transformation of spatial harmonics into a metamaterial's modes cause distortion of the spatial spectrum of an image transmitted and decrease the subwavelength resolution of the device. However, there is the possibility to completely eliminate the losses by means of tuning the layer thickness to the Fabry–Perot resonance. In this case, unlike the classical Fabry–Perot resonance that is achieved only at a certain angle of incidence of the beam, complete transmission of the incident light is observed at any angle of incidence, including complex angles (i.e., evanescent spatial harmonics). When the metamaterial's isofrequency surface is a plane that has the required orientation in the space of wave vectors [23], all metamaterial modes propagate with a fixed phase velocity strictly across the layer and do not depend on the angle of incidence. In other words, the reflection coefficient of such a superlens is zero for all spatial harmonics of radiation. Hence, a source can be located in the immediate vicinity of the lens boundary and the near field of this source will not be distorted by the waves reflected from the lens.

Restrictions imposed on the superlenses operating in the image canalization regime are identical to those imposed on the lenses formed by photonic crystals [22]: To obtain a high resolution, the smallest possible structure spacing must be used. However, in this case, selection of an operating frequency close to the bandgap boundary—a requirement that is mandatory for observation of negative refraction effects in photonic crystals—is not necessary [16–22, 31–34]. Consequently, the crystal-lattice spacing can be much smaller than the wavelength, thus allowing to obtain a sufficiently high subwavelength resolution.

2. IMPLEMENTING THE IMAGE CANALIZATION PRINCIPLE IN THE MICROWAVE BAND WITH THE USE OF A LAYER OF A MEDIUM COMPOSED OF WIRES WITH PERIODIC CAPACITIVE LOADS

For the *s* (transverse electric (TE)) polarization [23], the canalization principle was implemented in the

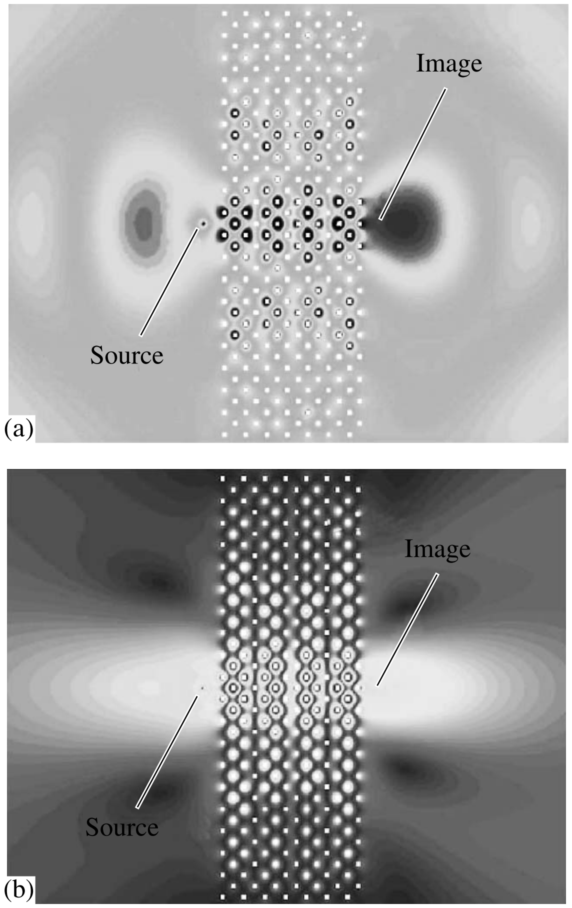

Fig. 4. Distributions of (a) the electric field and (b) the electric-field amplitude in the neighborhood of a superlens excited by a point source located close to the lens surface.

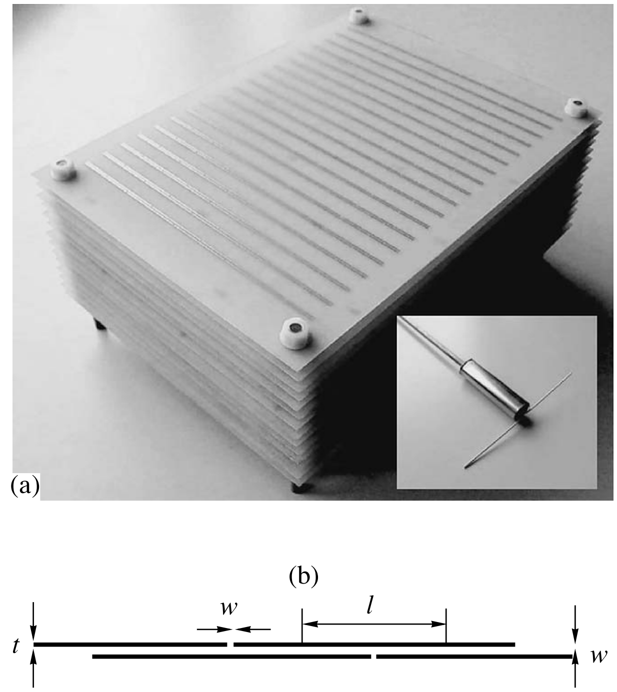

Fig. 5. (a) Photograph of the layer of an electromagnetic crystal formed by periodically loaded wires [23] and (b) geometry of a single wire with capacitive loads. The structure parameters are as follows: $l = 22$ mm, $t = 0.575$ mm, $w = 1.1$ mm, and the remaining parameters are the same as in Fig. 3. The operating frequency is 1.73 GHz.

microwave frequency band via the use of an electromagnetic crystal consisting of wires with periodically placed capacitive loads [35] (see Fig. 3a). The geometry and parameters of the superlens are presented in Fig. 3. The medium composed of wires with capacitive loads has a band gap at an extremely low frequency (the ratio between the wavelength and the lattice spacing is $\lambda/a = 14$) and does not contain any materials with high permittivity. The operating frequency of the superlens is chosen to be close to the boundary of the crystal's resonant band gap so that it corresponds to the flattest part of the isofrequency surface. The angle between the superlens surface and the lattice axes is 45°. As a result, the surface is orthogonal to the normal to this isofrequency surface. The layer thickness is chosen so as to satisfy the Fabry–Perot condition. The numerical calculation based on the local-field method has shown [23] that, for the chosen parameters, the layer of the wire medium with periodic loads transmits the image of a point source located close to its front surface to the back surface with a resolution of $\lambda/6$ (Fig. 4).

As seen from Fig. 4a, the image of this source appeared in antiphase. Such is the case because the layer thickness corresponds to half the wavelength in the structure. With the use of a lens of double thickness, an image can be obtained in phase. The near-field distribution of the source is transported from one surface to the other through a spatial channel that is formed inside the electromagnetic crystal in the direction from the source to the image. Owing to this effect, this principle of image transmission with superresolution was called in [23] the image canalization principle.

The theoretical estimates [23] were verified experimentally in [24], where the $\lambda/10$ resolution was achieved at a frequency of about 2 GHz. A wire medium with capacitive loads was implemented with the use of a stack of boards (Fig. 5a) with printed metal strips of certain dimensions (Fig. 5b). The dimensions were chosen so as to fit the capacitive impedance per unit length used in the calculations performed in [23]. However, measurements have shown that the fabricated crystal sample had a resonant band gap at frequencies lower than expected.

This means that the capacitive impedance of the fabricated sample exceeded the calculated value. Nevertheless, its ability to serve as a superlens remained at the same level. Furthermore, owing to lowering of the center frequency of the resonant band gap, the ratio between the operating wavelength and the structure spacing increased and, consequently, the superlens resolution improved.

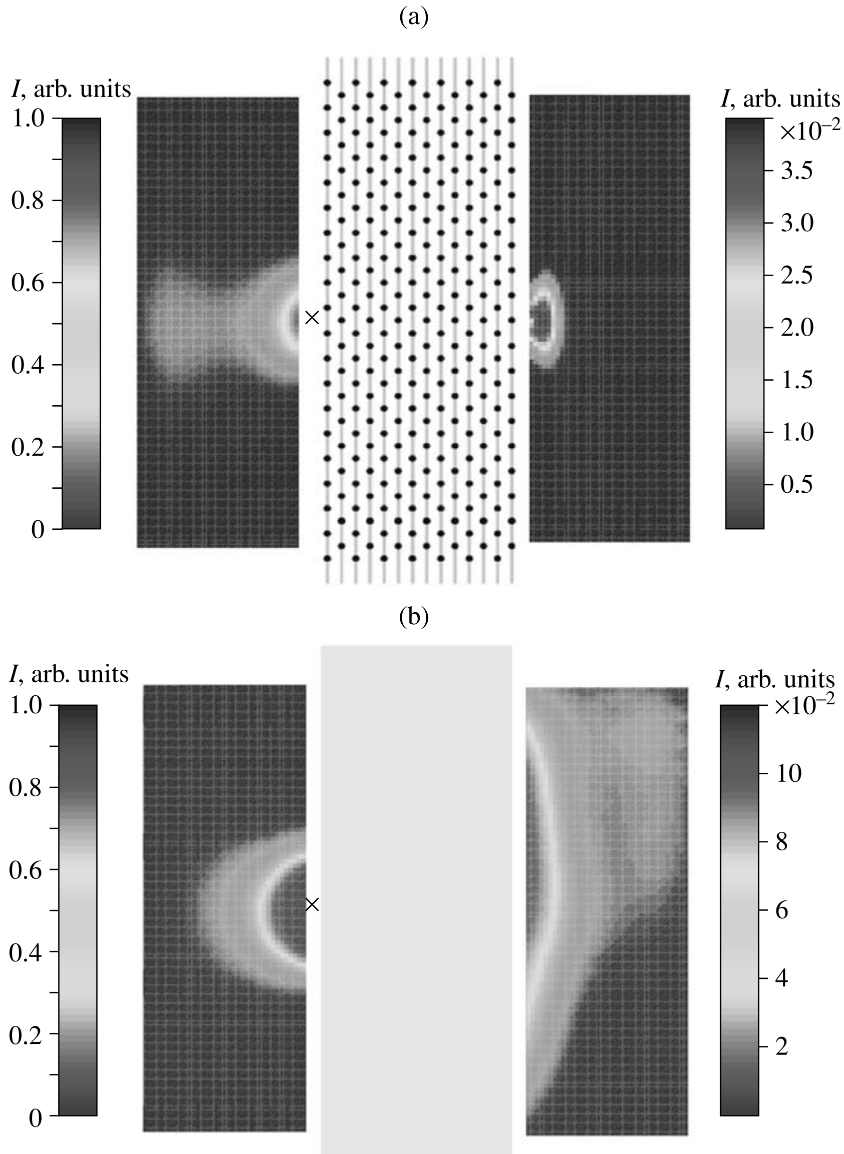

Fig. 6. Distributions of electric field intensity I (in arbitrary units) (a) in the neighborhood of a superlens excited by a dipole antenna located close to the lens surface and (b) in the absence of the superlens. The cross designates location of the source.

The near field in the neighborhood of the fabricated superlens was scanned when an exciting dipole antenna (see Fig. 5a) was brought to its surface. Another dipole antenna was used as a probe. The result of the field scan is presented in Fig. 6a. A clear and sharp maximum behind the layer's back surface confirmed the fact that the fabricated structure is a lens capable of forming an image with a subwavelength resolution. For comparison, the result of the field scan in the absence of the superlens is presented in Fig. 6b. The field maximum observed is much wider than that in the case of the superlens and, simultaneously, its radius is of the order of the half-wavelength, thus fitting the diffraction limit.

The radius of the image obtained with the superlens was estimated at the half-intensity level. The estimation has shown that the resolution is about $\lambda/10$. A better resolution could be achieved through an increase in the capacitive loads. However, in this case, increasing losses in the structure are unavoidable. Furthermore, the superlens bandwidth becomes narrower, thereby impeding the signal detection in the image region. In the performed experiment, the field intensity behind the layer's back surface was found to be 20 times less than the field intensity close to the source. This result is due to the fact that the dielectric material of printed circuit boards has high losses arising from a high intensity of the field inside the crystal (see Fig. 4b). Since the obtained image replicates the original one, it is fitting to presume image transmission with superresolution. Furthermore, the performed experiment shows that the

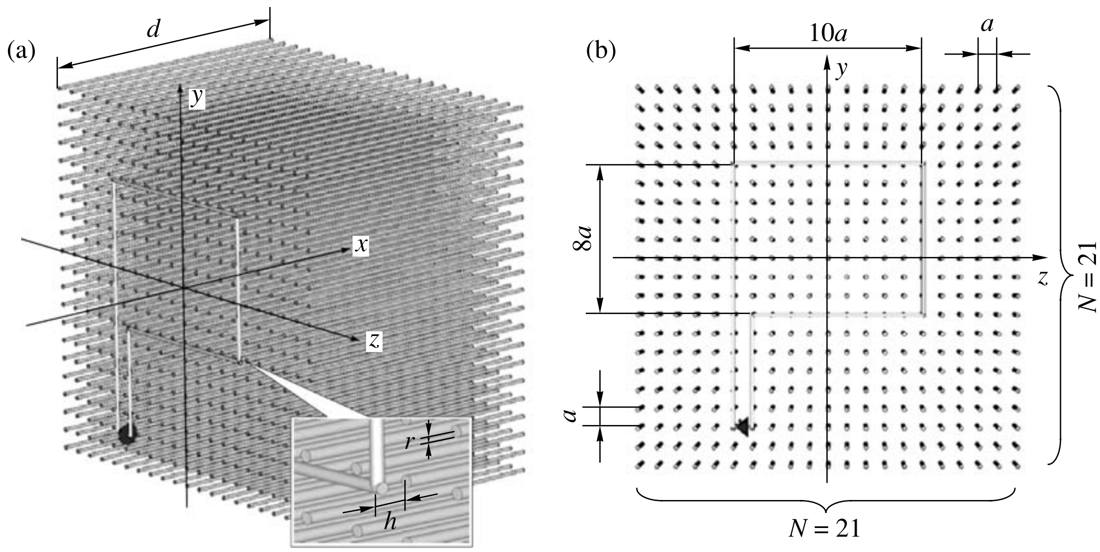

Fig. 7. Geometry of the wire-medium lens used for image transmission at a frequency of 1 GHz [25]: (a) perspective view and (b) front view. The structure parameters are as follows: $a = 10$ mm, $r = 1$ mm, $d = 150$ mm, and $h = 5$ mm.

canalization principle is insensitive to losses and that image transmission with superresolution is possible also when significant losses are introduced into the structure. By contrast, the resolution of Pendry's superlenses formed from the Veselago media is sensitive to the smallest losses [3].

3. IMPLEMENTING THE IMAGE CANALIZATION PRINCIPLE IN THE MICROWAVE BAND BY MEANS OF A WIRE MEDIUM

For the *p* (transverse electric (TM)) polarization, an excellent possibility for implementation of the canalization principle in the microwave band is provided by the simplest artificial medium formed by a lattice of parallel wires [36–39] (Fig. 7). This wire medium supports modes of an extremely specific type: the so-called transmission-line modes [39] that transfer the electromagnetic energy strictly along the wires with a fixed phase velocity equal to the velocity of light, while the wave vector of such a mode can have an arbitrary transverse component. Thus, the transmission-line modes have a perfectly flat isofrequency characteristic at microwave frequencies.

Comprehensive analytical, numerical, and experimental studies [25, 28, 30] have shown that a superlens comprising a layer of wires arranged perpendicularly to the layer surface (Fig. 7) transmits microwave images with a resolution equal to the doubled lattice spacing, which can be made much smaller than the wavelength. Everything depends exclusively on the cost of fabrication of such a lattice. The lens formed by a wire medium operates as a multiconductor transmission line or a set of uncoupled waveguides having subwavelength dimensions. This "telegraph" principle guarantees pixel-to-pixel transmission of images from one lens surface to the other. With the use of a wire medium, transmission of microwave images with the $\lambda/15$ resolution at frequencies close to 1 GHz has been demonstrated both numerically (Fig. 8) and experimentally (Figs. 9, 10) [25].

The bandwidth in which image transmission was observed was 18%. Furthermore, it was found that such a structure is practically insensitive to losses and, consequently, the lens can be as thick as necessary relative to the wavelength. The single restriction is the necessity of satisfying the Fabry–Perot resonance condition. (The lens thickness must be equal to an integer number of half-wavelength.)

4. IMPLEMENTING THE IMAGE CANALIZATION PRINCIPLE IN THE TERAHERTZ AND INFRARED BANDS

Superlenses formed by wires are unique devices for imaging with a subwavelength resolution in the microwave frequency band, where metals are practically perfect conductors. However, in the terahertz and infrared bands, a superlens with such geometry will operate under certain restrictions [29, 40] because metals have plasma (rather than conductor) properties at these frequencies. Numerical results [29] show that, with the use of a set of silver nanorods embedded into a chalcogenide-glass layer (Fig. 11), it is possible to transmit an image with the $\lambda/10$ resolution at a frequency of 30 THz over a distance approximately equal to the wavelength in glass (Fig. 12). Numerical calculations were performed with a near-field source shaped as the letters *IR*. This shape of the source was used to emphasize that the lens operates in the infrared band.

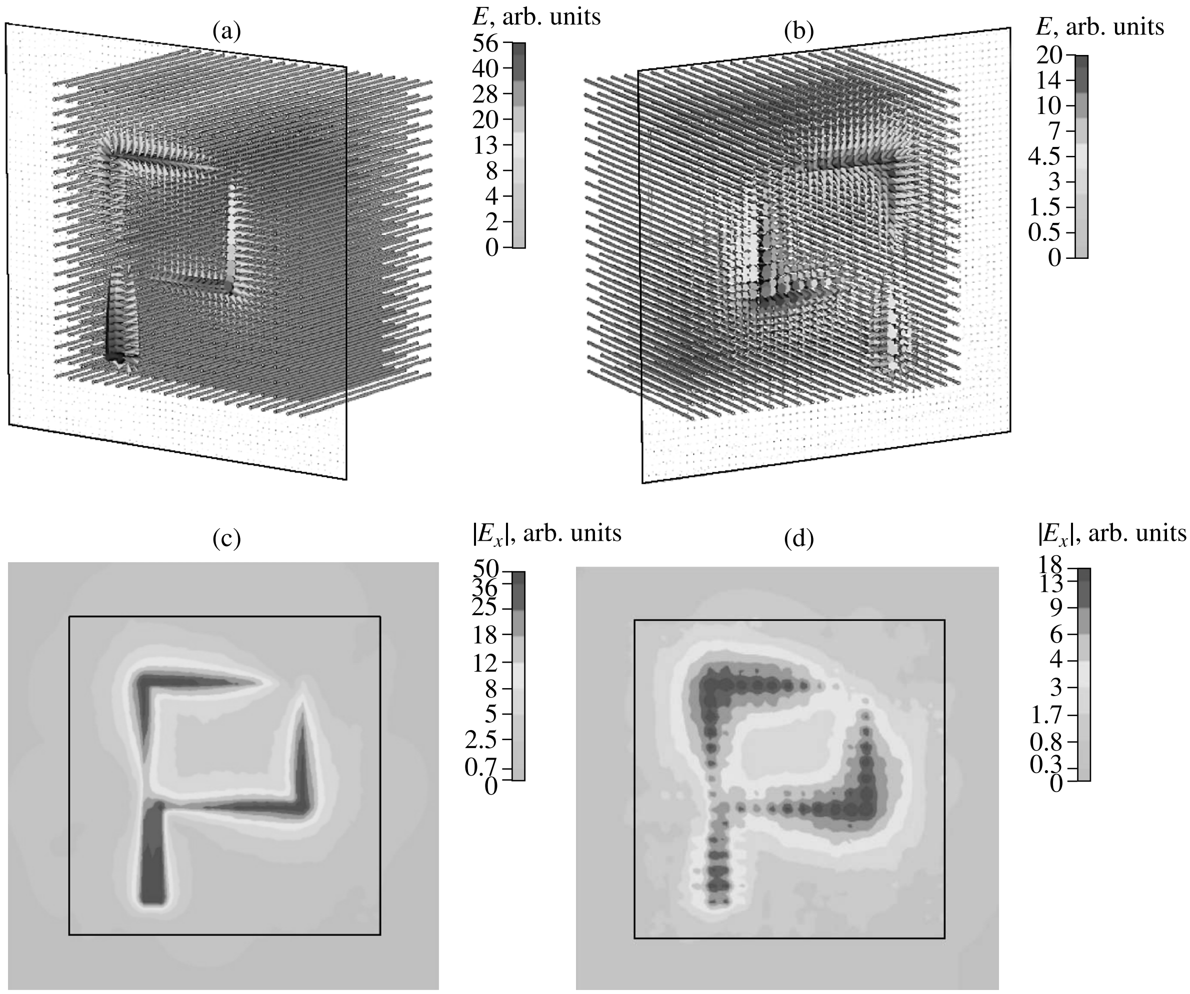

Fig. 8. Distributions of electric field E (in arbitrary units) and the absolute value of its normal component ($|E_x|$) (in arbitrary units) obtained with the use of numerical simulation [25]: (a, c) on the front surface of the wire-medium lens and (b, d) on the back surface of the lens.

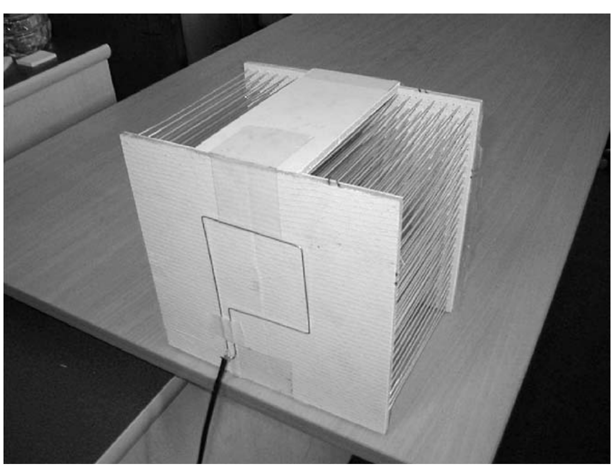

Fig. 9. Photograph of the experimental sample of a wire medium lens [25].

At lower frequencies, it is possible to obtain a higher resolution via the use of a structure of similar geometry. The results of a numerical simulation performed for a 36×73 lattice with a spacing of 1.3 μm are presented in Fig. 13. The lattice is formed from silver cylinders with a length of 38.8 μm and a radius of 130 nm that are embedded into a chalcogenide-glass layer and is designed for operation at a frequency of 5 THz. In this case, the resolution is $\lambda/20$.

To date, silver nanorods used to implement the canalization regime have not provided satisfactory results at frequencies above 30 THz, because the absolute value of the permittivity of silver is insufficient in this frequency band [40]. Hopefully, the canalization regime will be implemented at frequencies above 30 THz by means of using gold or aluminum nanorods. However, it is apparent that the canalization regime cannot be implemented at optical frequencies during the use of a medium composed of metal cylinders.

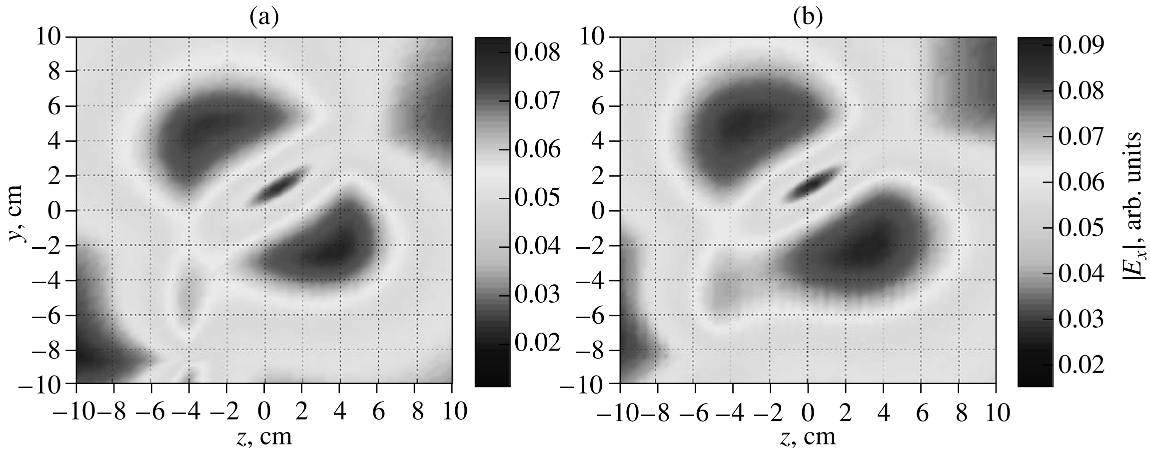

Fig. 10. Experimental results of the near-field scan (in arbitrary units): (a) on the front surface of the wire-medium (source plane) and (b) on the back surface (image plane).

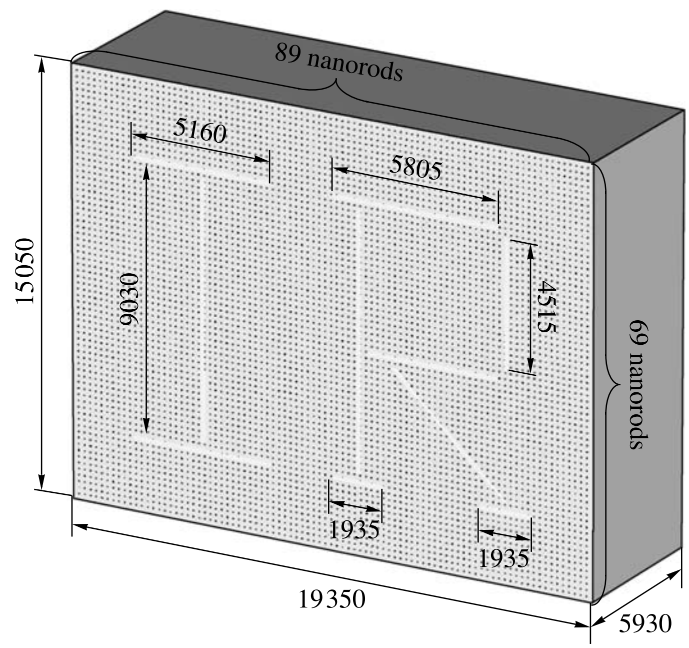

Fig. 11. Geometry of the lens used for image transmission at a frequency of 30 THz [29]. The lens is a chalcogenide-glass layer with embedded 21.5-nm-radius silver nanorods. All dimensions are in nanometers.

5. IMPLEMENTING THE IMAGE CANALIZATION PRINCIPLE IN THE RANGE OF VISIBLE LIGHT

In [26], an alternative layered metal–dielectric structure is proposed for implementing the image canalization principle at visibale range. Operation of this optical telegraph in the visibale range is similar to operation of a wire medium in the microwave frequency band. To understand this fact, let us consider certain properties of a wire medium in the microwave band. It is known that a wire medium (see Fig. 7a) can be described by the following tensor of spatially dispersed permittivity [39]:

$$\boldsymbol{\varepsilon}(\omega, k_x) = \varepsilon_0 \begin{pmatrix} \varepsilon(\omega, k_x) & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{1}$$

$$\varepsilon(\omega, k_x) = 1 - \frac{k_p^2}{k^2 - k_x^2}, \tag{2}$$

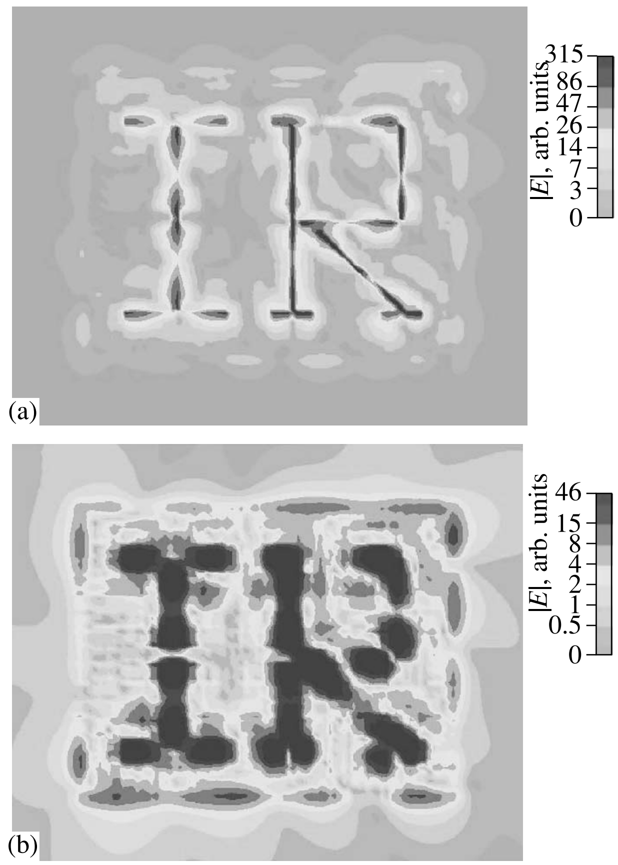

Fig. 12. Distributions of the absolute value of the electric field (in arbitrary units) on the (a) front and (b) back surfaces of the lens formed from silver nanorods at a frequency of 30 THz [29].

where the $0x$ axis is oriented along the wires, $k = \omega/c_l$ is the wave number of the host medium, $k_p = \omega_p/c_l$ is the wave number that corresponds to plasma frequency ω_p and depends on the lattice spacing and the wire radius, k_x is the component of the wave vector directed along the wires, c_l is the velocity of light, and ε_0 is the permittivity of the host medium.

For transmission-line modes, $k_x = k$ and permittivity (2) becomes infinitely large. Thus, these modes efficiently propagate in a medium with the permittivity expressed as

$$\boldsymbol{\varepsilon} = \varepsilon_0 \begin{pmatrix} \infty & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{3}$$

Consequently, to obtain the properties in the optical band that are identical to those in the microwave band, it is necessary to create a uniaxial crystal with permittivity described by formula (3). For isotropic composites, it is hardly probable to achieve very high values of permittivity in the optical band. For example, there are no natural materials with a permittivity of the order of 100 in the optical band. However, it seems plausible that a component of the permittivity tensor of the order of 100 or more can be obtained with the use of anisotropic artificial media. For example, in a layered metal–dielectric structure [41], one of the components of the permittivity tensor can have high values.

Let us consider the layered structure shown in Fig. 14. At low frequencies, such a structure can be described by the following permittivity tensor:

$$\boldsymbol{\varepsilon} = \begin{pmatrix} \varepsilon_{\parallel} & 0 & 0 \\ 0 & \varepsilon_{\perp} & 0 \\ 0 & 0 & \varepsilon_{\perp} \end{pmatrix}, \tag{4}$$

where

$$\varepsilon_{\perp} = \frac{\varepsilon_1 d_1 + \varepsilon_2 d_2}{d_1 + d_2}, \quad \varepsilon_{\parallel} = \left[\frac{\varepsilon_1^{-1} d_1 + \varepsilon_2^{-1} d_2}{d_1 + d_2}\right]^{-1}. \tag{5}$$

To obtain $\varepsilon_{\perp} = 1$ and $\varepsilon_{\parallel} = \infty$ and create a material with permittivity tensor (3), which is necessary for implementing the canalization principle, it is sufficient to choose parameters of the layered structure such that $\varepsilon_1/\varepsilon_2 = -d_1/d_2$ and $\varepsilon_1 + \varepsilon_2 = 1$. It is seen from the first equation that one of the layers must have a negative permittivity; i.e., the structure must consist of alternating metal and dielectric layers. For example, it is possible to choose $\varepsilon_1 = 2$, $\varepsilon_2 = -1$, and $d_1/d_2 = 2$ or $\varepsilon_1 = 15$, $\varepsilon_2 = -14$, and $d_1/d_2 = 15/14$.

It is significant that the structure required for implementation of the canalization regime cannot be created from layers of equal thickness, because the condition $\varepsilon_1/\varepsilon_2 = -d_1/d_2 = -1$ leads to the inequality $\varepsilon_1 + \varepsilon_2 = 0 \neq 1$. Pendry's multilayered metal–dielectric structures with layers of equal thickness (described in [10–12]) have optical properties that differ from the properties of the layered structures required for implementation of the image canalization regime.

It has been noted in [12] that layered materials with $d_1 = d_2$ and $\varepsilon_1 = -\varepsilon_2$ (as in [10–12]) correspond to the case of $\varepsilon_{\perp} = 0$ and $\varepsilon_{\parallel} = \infty$ and in fact behave as a wire lattice embedded into a material with zero permittivity. Such a structure is an anisotropic analogue of the so-called material with zero refractive index [42]. This anisotropic medium is not matched with free space, because its permeability has a trivial value (μ equals unity rather than zero, as required for matching of such media). When the wave impedances of the medium and the ambient space are unmatched, a high level of reflections from the layer of such a material is observed. This circumstance sets an upper bound on the admissible layer thickness, as was discussed above. In contrast to Pendry's structure, reflections from the proposed structure operating in the canalization regime are absent because the Fabry–Perot resonance condition is fulfilled for all possible angles of incidence of the plane

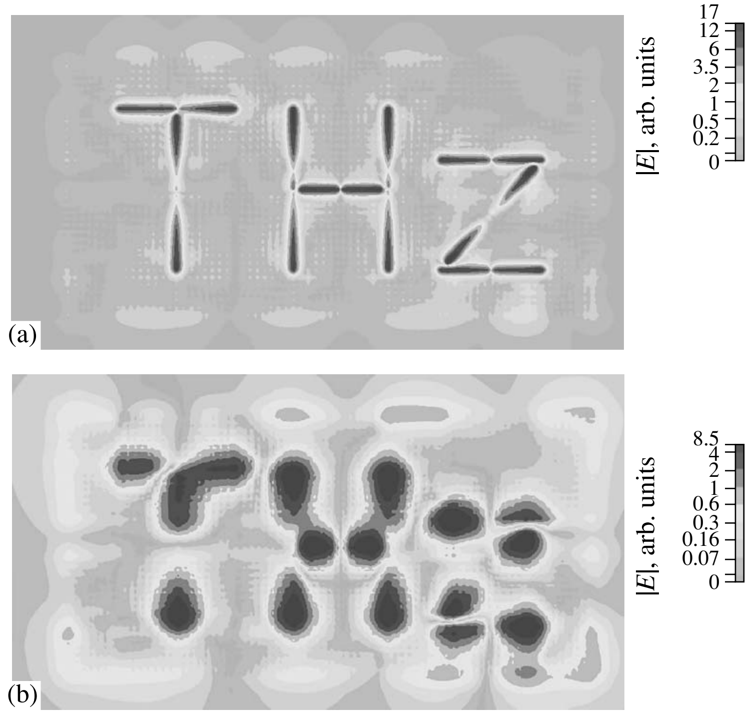

Fig. 13. Distributions of the absolute value of the electric field (in arbitrary units) on the (a) front and (b) back surfaces of the lens formed by silver nanorods at a frequency of 5 THz.

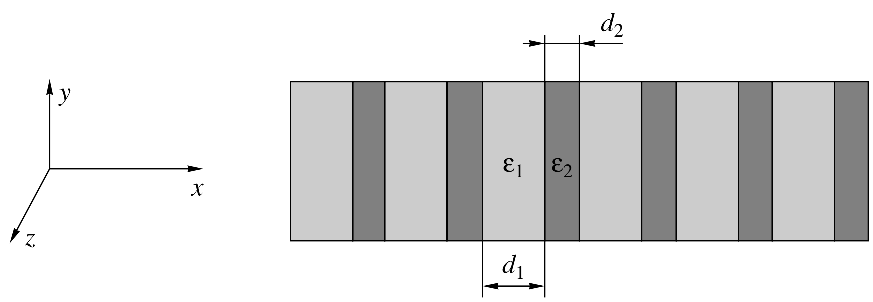

Fig. 14. Geometry of the multilayered metal–dielectric structure used for implementation of the canalization principle in the optical band [26].

wave impinging onto the slab, including complex angles.

To demonstrate that image transmission with subwavelength resolution can be implemented in the canalization regime by means of the proposed layered metal–dielectric structure, numerical simulation [26] has been performed. A near-field source representing a current loop shaped as the letter *P* was located at a distance of 20 nm from a 300-nm-thick superlens consisting of alternating layers with the permittivities $\varepsilon_1 = 2$ and $\varepsilon_2 = -1$ and the thicknesses $d_1 = 10$ nm and $d_2 = 5$ nm. The radiation wavelength was chosen to be 600 nm. A material with a permittivity equal to –1 at a wavelength of 600 nm can be created via addition of colloidal silver to a low-loss dielectric material [43, 44]. Glass can be used as a dielectric material with a permittivity equal to +2. The structure geometry is presented in Fig. 15.

Electric-field distributions in the planes parallel to the lens surface, which are presented in Fig. 16, clearly demonstrate image transmission with a 30-nm ($\lambda/20$) resolution. The free-space field at a 20-nm distance from the source (Fig. 16a) is practically identical to the field on the front surface of the lens (see Fig. 16b). This circumstance means that reflection from the superlens surface is negligibly low. To the left of the lens, the main contribution to the field is made by the waves diffracted at the edges and corners of the lens. The field distribution on the back surface is shown in Fig. 16c. The image is clearly distinguishable, despite the presence of distortions introduced by plasmon-polariton modes excited on this surface. The field of these modes

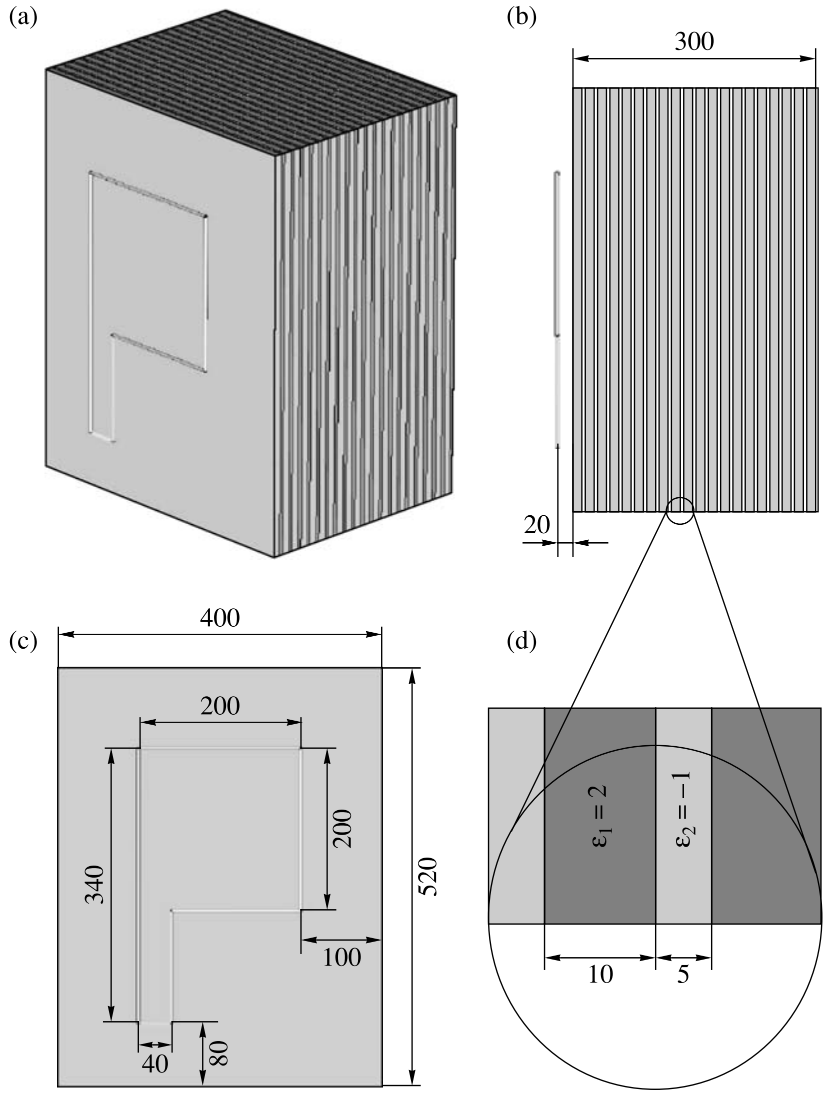

Fig. 15. Geometry of the superlens formed form a multilayered metal–dielectric metamaterial and used for numerical simulation [26]: (a) perspective view, (b) side view, (c) front view, and (d) an enlarged fragment of the inner structure. All dimensions are in nanometers.

decreases rapidly with distance, so that their contribution becomes negligible at a distance of 20 nm from the back surface and the transmitted field contains only the useful information on the image details (see Fig. 16d).

The resolution of the multilayered structure proposed in [26] is restricted by its spacing $d = d_1 + d_2$ in the direction perpendicular to the lens surface, in contrast to the case of a lens formed by a wire medium when the resolution is determined by the spacing along the lens surface. The initial periodic structure can be modeled as a homogeneous uniaxial dielectric material with permittivity tensor (4) only if each component of the wave vector varies in a restricted range. This restriction has been confirmed in [26] through calculation of the isofrequency characteristics of the metamaterial under consideration, which was treated as a 1D photonic crystal consisting of metal and dielectric layers. It should be noted that the restriction on resolution caused by the structure periodicity is observed also in the cases reported in [10–12] and can compete with the restriction caused by losses in the material.

In [26], the calculated isofrequency characteristics were used to predict that an improved resolution of the order of $\lambda/60$ can be obtained at a wavelength of 600 nm for a multilayer structure consisting of layers with permittivities $\varepsilon_1 = 15$ and $\varepsilon_2 = -14$ and thicknesses $d_1 = 7.76$ nm and $d_2 = 7.24$ nm. Such a structure can be created with the use of silicon as a dielectric material and silver as a metal. However, the desired result can be achieved only if this structure is fabricated with a high accuracy of surface polishing (with an allowable error of no more than 0.05 nm). The preceding structure (see Fig. 15) is an order of magnitude less sensitive to surface irregularities. In two proposed variants of super-

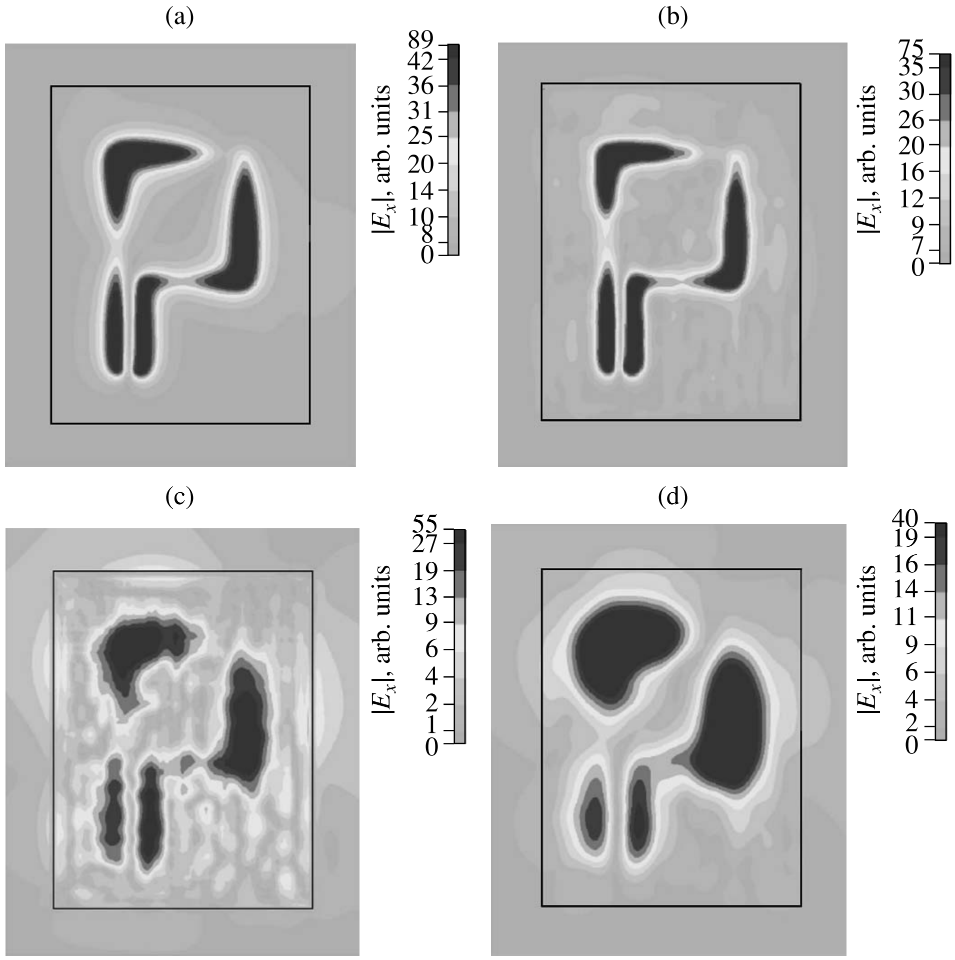

Fig. 16. Distributions of the absolute value of electric-field component $|E_x|$ (in arbitrary units) normal to the superlens surface [26]: (a) in free space at a distance of 20 nm from the source, (b) on the front surface, (c) on the back surface, and (d) in free space at a distance of 20 nm from the back surface

lenses, the losses in silver are minimized by selection of the value of the operating wavelength (600 nm) corresponding to the minimum absorption. However, according to the numerical estimates, losses lead to a significant decease in resolution. By analogy with the ideas reported in [12, 43], this problem can be solved through the use of optically active materials.

The entire frequency band within which multilayered metal–dielectric structures can be used for canalization of near-field images has not been studied yet. However, it is expected that all optical frequencies up to the middle infrared band, including the high-frequency infrared spectrum, where metal cylinders are not applicable for canalization, will be available. Thus, with the use of metal-wire media [25] and multilayered metal–dielectric structures [26], it will be possible to create devices for image transmission with a subwavelength resolution in the entire frequency spectrum, including microwave and optical bands.

CONCLUSIONS

It has been shown that the image canalization principle can be implemented in the microwave, terahertz, and optical frequency bands with the use of different types of metamaterials. The possibility of image transmission with a subwavelength resolution over significant distances has been demonstrated. We managed to overcome the diffraction limit on the resolution of lens-based imaging devices, an obstacle that had remained unavoidable for a long time.

Metamaterials capable of transmitting images in the microwave, terahertz, and optical frequency bands can be used in medicine, in near-field microscopy, and as components of high-technology devices. As the most important example, it suffices to mention that superresolution lenses can be used to increase the capacity of optical storages (DVDs) by decreasing sizes of their recording regions, which are now restricted by the diffraction limit.

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