Applied Physics Letters

RESEARCH ARTICLE | NOVEMBER 17 2003

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Appl. Phys. Lett. 83, 4122–4124 (2003)
https://doi.org/10.1063/1.1627474

Focusing of millimeter-wave radiation beyond the Abbe barrier

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(Received 6 June 2003; accepted 18 September 2003)

A hemispherical focusing system for millimeter waves is presented. Focusing of the beam to a spot of ~0.3λ was obtained in the frequency range from 100 to 200 GHz. Compared to the scanning near-field optical spectroscopy, the system allows simultaneous imaging of extensive subwavelength objects. As an example, a double slit of size $d=1$ mm was clearly resolved using a radiation with a wavelength $\lambda=2$ mm. Using future optically dense lenses, a resolution of the order λ/100 seems to become possible. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1627474]

Known as the Abbe barrier, the diffraction limit indicates that the resolution of an optical microscope cannot be better than the wavelength of the radiation; more precisely,[1]

$$\Delta_{\min}=0.61\lambda/\sin\alpha, \tag{1}$$

where α is the aperture angle of the optical device and λ is the wavelength. This equation directly follows from the Fourier analysis of the optical image formation and leads to the conclusion that all-Fourier components with spatial frequencies f such that $f>1/\lambda$ must decay exponentially. However, a device managing to recover the decaying components would in principle be able to focus the light into a subwavelength spot. It has been suggested recently[2,3] that a slab of material with a negative refractive index would overcome the limitation of Eq. (1), effectively recovering the evanescent Fourier components. Recently, a metamaterial with negative refractive index has been constructed,[4] which indeed revealed focusing properties.[5] Another theoretical possibility to overcome the diffraction limit includes specially constructed photonic crystals, for which the superlens effect has been demonstrated numerically.[6]

The modern technique to obtain spatial resolution beyond the diffraction limit is scanning near-field optical microscopy (SNOM).[7] Experimentally, high resolution is achieved using either light sources or detectors having dimensions much smaller than the radiation wavelength. Within this technique, the resolution as high as 1/60 of the wavelength of the radiation has been demonstrated for microwave frequencies.[8] Another possibility to obtain subwavelength resolution utilizes a highly focused near-field spot of a hemispherical lens with a high refractive index.[9] This solid-immersion-lens technique has been developed to dramatically increase the read/write density of the optical memories and has led to a resolution improvement $\Delta\sim0.4\lambda$ in the optical range.[10] Recently, numerical simulations revealed a high transmission efficiency of a hemispherical system.[11]

Here, we demonstrate that in the near-field of a hemispherical lens a resolution of ~0.3λ can be obtained for millimeter-wave frequencies. Moreover, compared to scanning microscopy, this arrangement allows simultaneous imaging of a finite area close to the focus. As an example, the double slit of size $d=1$ mm could be clearly resolved using the radiation with the wavelength $\lambda=2$ mm. The significantly improved resolution at millimeter wavelengths results from the fact that in this frequency range, the refractive index of all materials is much higher than for visible light due to the ionic polarization of the lens material, which is superimposed onto the electronic polarization processes. The construction of lenses with $n\sim100$ seems to be realistic in the millimeter wave regime.

The optical arrangements of the present experiment is shown in Fig. 1. The millimeter-wave radiation in the frequency range from 100 to 200 GHz ($\lambda=3$–1.5 mm) is generated using a set of three backward-wave-oscillators and the signal is detected by an opto-acoustic detector (Golay cell). The experimental setup is part of quasioptical submillimeter-wave spectrometer, described elsewhere.[12] The Teflon™ lens (t) with a focal ratio F_t/D_t close to unity, focuses the beam to a diffraction-limited spot. Without a hemispheric sapphire lens the spot size would be approximately one wavelength, see the lowest frame of Fig. 2. The spherical form of this lens conserves the converging wavefront behind the sapphire–air interface. Due to higher optical density of sapphire ($n_s\simeq3.1$ in this frequency range), the beam is focused to a spot of a smaller characteristic size ($\Delta\sim\lambda/n_s$) inside the hemisphere. The ideal spherical form is crucial because a plane-parallel slab of the same material would defocus the sharply converging beam due to Snell's refraction law on the sapphire–air interface. This would finally lead to the same spot size $\Delta\sim\lambda$, as without the hemisphere. During the experiments, the

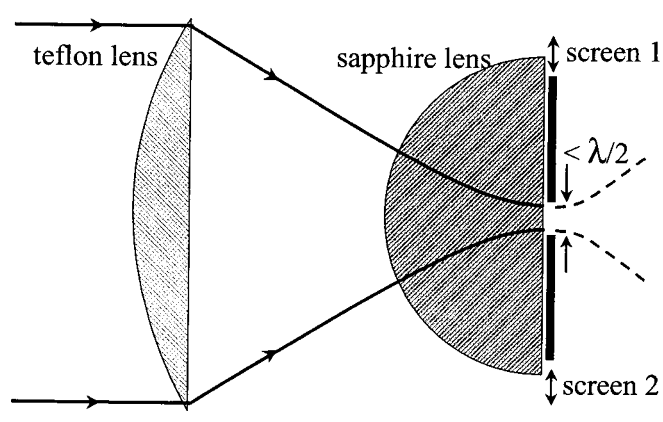

FIG. 1. Scheme of the optical arrangement that focuses light beyond the diffraction limit. The sapphire lens has an ideal hemispherical form.

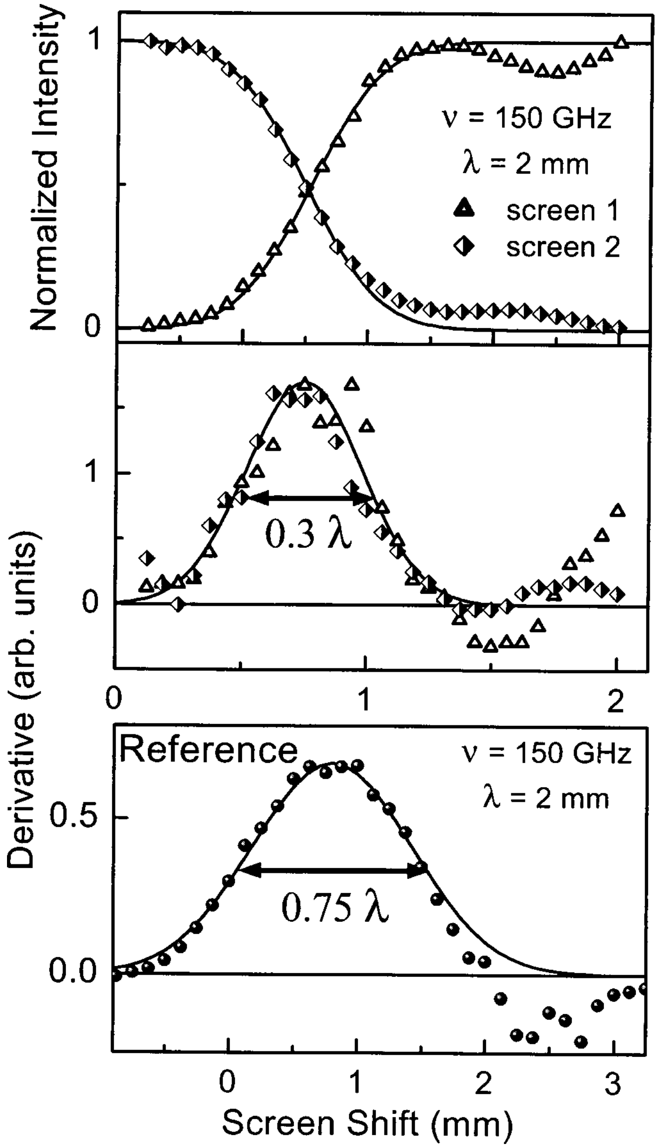

FIG. 2. Upper panel: Signal intensity as a function of the screen positions (Fig. 1). Middle panel: Derivative of the signal in the upper panel showing the structure of the focal spot. Lower panel: Structure of the focal spot without sapphire hemisphere. The symbols in all frames represent the experimental data, the solid lines correspond to fits using Gaussian distributions.

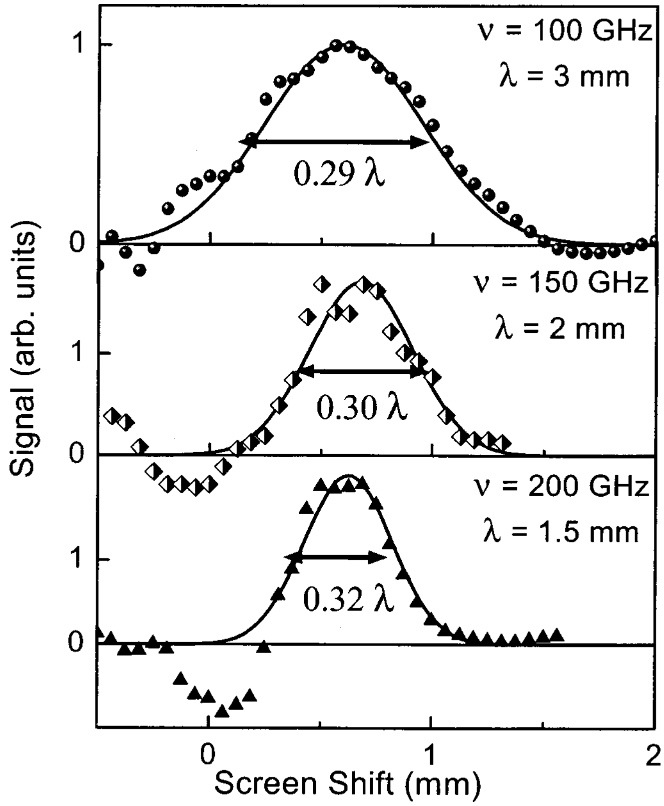

FIG. 3. Characteristic size of the focal spot for three different frequencies. Symbols: experiment; lines: fits using Gaussian distributions. Deviations between theory and experiment are due to diffraction effects.

whole system is adjusted to obtain a focal spot close to the flat surface inside the sapphire. Finally, using boundary conditions at the sapphire–air surface we see that the distribution of the electromagnetic fields cannot change abruptly directly behind the surface; that is, are limited to a subwavelength spot $\Delta \sim \lambda / n_s$.

Figure 2 shows the results of focusing the radiation with frequency 150 GHz ($\lambda = 2.0$ mm). In this experiment, the intensity of the transmitted signal is recorded as function of the screen position. As a result, a characteristic step function is generated, which is shown in the upper panel of Fig. 2. The derivative of this step produces the spatial distribution of the focal spot and the middle panel of Fig. 2 demonstrates the effect of focusing to a spot of $\Delta \sim 0.3\lambda$; that is, substantially below the limit imposed by Eq. (1).

As a reference, the lower panel of Fig. 2 shows the spatial distribution of the focal spot in the absence of the sapphire focusing system. In this case a conventional spot size of about 1.5 mm$=0.75\lambda$ is achieved, in agreement with the diffraction criteria. Therefore, an improvement of the resolution by a factor of 2.5 can be deduced, which is in rough agreement with expected squeezing of the focus by the refractive index of sapphire ($n_s \simeq 3.1$). The deviation probably results from finite thickness of the screen and from spherical aberrations of the Teflon lens.

We recall that a similar technique is utilized in the visible frequency range to increase the density of the optical memories.[9,10] The hemispherical lens made of optical glass with $n = 1.83$ allowed to obtain a focal spot $\Delta \sim 0.38\lambda$. The increased resolution of the present experiment results from the increased diffraction index at low wavelengths due to ionic polarizability. It would be worthwhile to search for new lens materials with high refractive indices and low losses. The subwavelength resolution of the present technique may be improved considerably both in visible range and in microwaves with the developments of photonic crystals. Recent calculations revealed[13] that effective refractive indices within the transmissions bands of two-dimensional photonic crystals can be as high as $n \sim 7$.

The experiments represented in Fig. 2 were repeated for frequencies of 100 GHz ($\lambda = 3.0$ mm) and 200 GHz ($\lambda = 1.5$ mm). As shown in Fig. 3, the focusing characteristics of the system are not limited to a single frequency, and a focal spot substantially below the diffraction limit ($\Delta \sim 0.3\lambda$) can be achieved in the complete frequency range.

Finally, the experimental arrangement in Fig. 1 is not limited by just obtaining the focal spot well below one wavelength, but in addition opens new possibilities for optical microscopy. Due to Helmholtz reciprocity theorem,[1] the

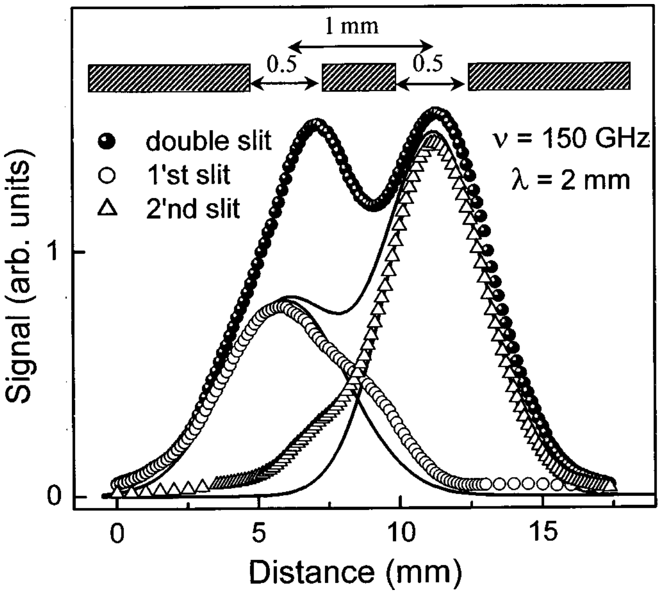

FIG. 4. Spatially resolved image of the double slit with $d=1$ mm in size (inset). Solid lines represent Gaussian fits to experimental data (symbols). The effective slit distance in the image corresponds to the magnification ~ 5.

electromagnetic fields must remain the same after interchanging source and detector. In this case, the focusing system works as a microscope with subwavelength resolution. It can also be expected that the increased resolution is not limited to the point at the optical axis, but is retained for a finite region near the focus. Therefore, placing a spatially-inhomogeneous subwavelength object near the focal plane, the magnified image of this object will appear on the (coordinate-sensitive) detector. To prove this point, we illuminated the system of Fig. 1 from the right-hand side, put a double-slit structure instead of the screens in the focal plane and recorded the spatial dependence of the detector signal placed on the left. The results presented in Fig. 4 demonstrate a well-resolved double-slit structure of 1 mm dimension using a radiation with a wavelength $\lambda=2$ mm. Because our detector is not position sensitive, these data have been recorded changing the position of the Teflon lens. We stress however, that a position-sensitive detector would simultaneously produce the picture of the object without a point-to-point imaging, as is done in scanning microscopy.[7]

The investigations at millimeter-wave frequencies are especially important in medicine and biology because of relative transparency of many materials in this range and the possibility to carry out *in vivo* imaging.[14] In addition to the spectral resolution, high spatial resolution is generally demanded due to the smallness of the samples. Therefore, subwavelength resolution of the hemispherical system can find a broad field of applications in these investigations. The resolution presented here can be further improved using transparent materials with even higher refractive indices compared to sapphire. Fully exploiting the limit of Eq. (1) and using a focusing system manufactured from ZrO_2/Y_2O_3 ($n \simeq 5.1 + 0.02i$),[15] a spot size as low as λ/8 can be achieved. Presently the search for materials with high dielectric constants and low losses in the megahertz and gigahertz regimes yielded compounds with dielectric constants $\epsilon \approx 50$ ($n \simeq \sqrt{\epsilon}$).[16] Recently the observation of colossal dielectric constants ($\epsilon \approx 10^5$) has been reported in a perovskite-derived materials.[17] However, it has been argued[18] that this unusually large values are extrinsic in nature and are due to charge accumulation in grain boundaries or contacts. Nevertheless, new materials with refractive indices as high as 100 and characterized by low losses could be available in the near future. Hemispherical lenses of these future materials would yield an optical resolution of λ/100, comparable to what can be obtained in SNOM.

In conclusion, the hemispherical focusing system from an optically dense material has been applied to millimeter-wave frequencies. The possibility to focus the radiation beyond the diffraction limit is demonstrated. In the present experiment, the values $\Delta \sim 0.3\lambda$ were obtained for frequencies 100–200 GHz. In addition, coordinate-sensitive detectors would allow to image simultaneously subwavelength objects around the focus. In the present experiments, a double slit of the size $d=1$ mm was clearly resolved using a wavelength $\lambda=2$ mm.

This work was supported by BMBF (13N6917/A-EKM).

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