Refraction contrast imaging with a scanning microlens

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We demonstrate subwavelength spatial resolution with a scanning microlens operating in collection mode with a large-area detector. Optical contrast is created by refraction of off-axis light rays at angles larger than the maximum collection angle. With a microfabricated silicon microlens 10 μm in diameter, we measure spatial resolution due to refraction contrast of $\lambda/4.3$ at a wavelength of $\lambda = 10.7$ μm. A model based on ray tracing is developed to explain our result, and we show that lens diameter and index of refraction limit resolution for large emission and collection angles. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1377318]

Micromachining techniques have enabled the fabrication of lenses with diameters comparable to the wavelength of light. Microlenses that are many wavelengths in diameter are used for collimation of fiber optics, wave-front sensing, and fill-factor improvement in detectors. Microlenses are also used for high-spatial-resolution solid-immersion microscopy, where light is focused through a solid-immersion lens (SIL) with a high index of refraction held close to the sample surface.[1–3] Spherical aberration in a lens is inversely proportional to the radius of curvature, making microlenses more tolerant to wave-front errors than large lenses.

As the diameter of a microlens is reduced, the ability of the lens to focus and collect light is affected. It has been shown previously how focusing in a transmitting microlens is changed when the lens diameter becomes comparable to the wavelength.[4,5] In a spherical lens, the field of view from which light is collected decreases with lens diameter. Microfabricated lenses with small fields of view can be used to direct beams of light by refracting off-axis rays. Small movements of a microlens in front of an optical fiber or vertical-cavity surface-emitting laser have been used for beam steering, optical interconnection, and optical switching.[6–9]

In this letter, we demonstrate a mode of operation in which spatial resolution of a scanning microlens operated in collection mode with a large-area detector is determined by refraction of off-axis rays at angles that become larger than the maximum collection angle. We demonstrate resolution of $\lambda/4.3$ at $\lambda = 10.7$ μm with a 10-μm-diam Si microlens scanned over a $\lambda/10$ diam tapered fiber tip used as a light source. Modeling is used to explain our results and show how resolution depends mainly on lens diameter and index of refraction for the case of large emission and collection angles.

The field of view of a lens is directly proportional to the square root of its focal length. As the focal length is reduced, the area in the object plane that can be imaged onto a detector without significant field curvature is also reduced. For a large hemispherical SIL, in which light is focused to a spot at the geometrical center of the lens with radius a and index of refraction n, the radius R of the field of view is given by

$$R = \sqrt{\frac{2a\Phi}{n(n-1)\sin^2\theta}}, \tag{1}$$

where Φ is the maximum acceptable wave-front aberration and θ is the maximum angle of convergence within the lens.[10] The spot size of the SIL is limited by diffraction to approximately $\lambda/(2\ \mathrm{NA})$, where $\mathrm{NA} = n \sin\theta$ is the numerical aperture and n is the index of refraction of the SIL. Setting R equal to the half width of a focused spot, the field of view for a spherical lens with a maximum aberration of $\lambda/4$ becomes comparable to the diffraction-limited spot size in air when the lens radius is on the order of

$$a \approx n(n-1)\frac{\lambda}{8}. \tag{2}$$

A Si microlens ($n = 3.4$) with a diameter of less than 20 μm and operated at a wavelength of $\lambda = 10$ μm has an aberration-limited field of view less than the diffraction-limited spot size.

We tested the spatial resolution due to refraction contrast of a 10-μm-diam hemispherical Si microlens by scanning it above a point source of $\lambda = 10.7$ μm light. The Si microlens is fabricated from single-crystal silicon using a photoresist reflow and reactive ion etching technique.[11] The 10-μm-diam lens is mounted on a Si film and has a total thickness approximately equal to the radius of the lens. The point source is a tapered, gold-coated chalcogenide glass fiber coupled to a CO_2 laser operating at $\lambda = 10.7$ μm. A 1.0-μm-diam aperture is opened in the gold-coated fiber to create a $\lambda/10$ source. The tip is positioned at the focus of a BaF_2 collection objective ($\mathrm{NA} = 0.45$), as shown in Fig. 1. The microlens is scanned above the fixed fiber tip on a three-axis piezoelectric stage, and a separation of less than 0.1 μm is maintained by feedback from a tuning fork mounted on the fiber. Light emitted from the fiber tip and coupled into the microlens is collected by the objective and measured by a liquid-nitrogen-cooled large-area HgCdTe detector.

The $\lambda/10$ source is measured to have a full width at half maximum (FWHM) of 2.5 μm, corresponding to $\lambda/4.3$ reso-

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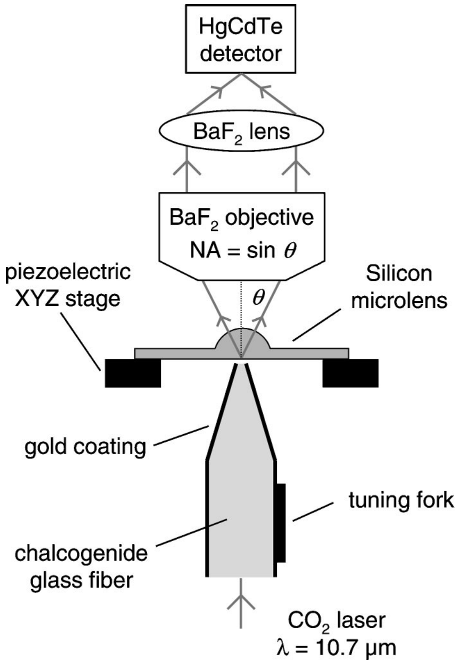

FIG. 1. Expiermental setup used for refraction contrast imaging with a scanned Si microlens showing the stationary chalcogenide glass fiber source and BaF_2 objective with maximum collection angle $\theta = 46.7°$ (NA=0.45).

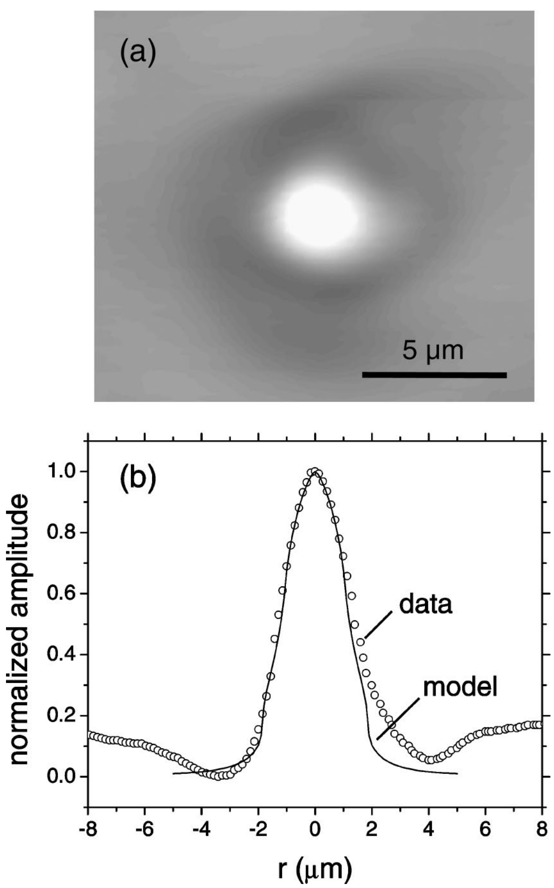

FIG. 2. (a) Refraction contrast image of the $\lambda/10$ tapered fiber tip taken with a scanning 10-μm-diameter Si microlens. (b) Normalized line scan through the image. The solid line plotted with the data is the result of a three-dimensional model of refraction in the lens with an offset in lens thickness equal to 10% of the diameter.

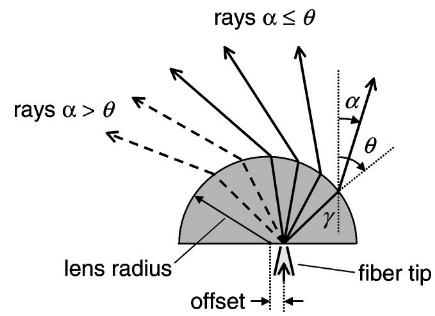

FIG. 3. Refraction of rays emitted at angles γ from a source that is offset from the geometrical center of the lens. Rays refracted at angles α less than the maximum collection angle θ are collected (solid), while lines with angles α greater than θ are not (dashed).

lution. Figure 2(a) shows a refraction contrast image of the fiber tip taken with the scanning microlens, and Fig. 2(b) shows a line trace through the image. When the microlens is centered over the fiber tip, collection by the objective is a maximum. As the lens is laterally offset from the source, light from the fiber tip is refracted by the microlens at angles larger than the maximum collection angle θ of the objective. With still larger offsets, the rays are totally internally reflected at the lens surface. The collected light reaches a minimum when the source is near the edge of the microlens and increases slightly to a level limited by total internal reflection at the planar exit surface of the thin Si film surrounding the microlens. The power collected through the lens when it is centered over the tip is a factor of approximately 3.5 greater than that collected over the plane surface.

The spatial resolution of refraction contrast imaging with a scanning microlens can be modeled with ray tracing when phase differences at the lens surface are small. This condition holds for emission from an oscillating electric dipole in a medium of index n when $d \geqslant \lambda/(\pi n)$.[12] For $\lambda = 10.7$ μm and for Si with $n = 3.4$, the condition is satisfied when $d \geqslant 1.0$ μm. Light emitted from a point source at an angle γ to the vertical is refracted by a hemispherical lens at an angle α to the vertical given by Snell's law, as shown in Fig. 3. When α is less than the maximum collection angle θ, the ray is collected by the objective and measured by the detector. As the ray is refracted at angles α greater than θ, it is no longer collected by the objective, and this is the source of optical contrast. The spatial resolution can be estimated from the offset of a point source necessary to refract a ray emitted at $\gamma = 0°$ beyond the maximum collection angle θ. At this point, half of the emitted light is no longer collected by the objective if all of the light is collected when the source is on axis. The FWHM is then related to $\mathrm{NA} = \sin\theta$ and lens diameter d according to

$$\sin^{-1}(\mathrm{NA}) = \sin^{-1}\left(\frac{n\mathrm{FWHM}}{d}\right) - \sin^{-1}\left(\frac{\mathrm{FWHM}}{d}\right). \qquad (3)$$

This approximate model of refractive contrast imaging can be improved by considering the angular dependence of emission from a small source and by including refraction in three dimensions and total internal reflection. The emitted intensity of the source is assumed to follow a $\cos^2\gamma$ distribution typical of an oscillating electric dipole.[12] Emitted and refracted rays are traced over three dimensions, and the results calculated for the experimental conditions are plotted as the solid line in Fig. 2(b) with a thickness offset of 10% in diameter. The results show good agreement with the experimental data. The main differences are in the regions far from the maximum, where light in the experiment is refracted by the thin film around the lens.

For the case of large emission and collection angles ($\sin\theta$ and $\sin\gamma$ close to 1), a ray emitted at $\gamma=0°$ from a point offset a distance x from the lens axis is totally internally reflected when $2x/d=1/n$. Since the resolution can be no better than this distance, we can write $\mathrm{FWHM}/d\approx 1/n$. For Si with $n=3.4$, total internal reflection limits resolution to $\mathrm{FWHM}/d\approx 0.29$. This estimate agrees with more-detailed calculations from the three-dimensional model and shows that the resolution in this case is inversely proportional to the refractive index and directly proportional to the diameter of the lens.

In summary, we describe an optical imaging technique based on scanning a microlens with a small field of view. A microfabricated Si microlens 10 μm in diameter is used to image a $\lambda/10$ source with a wavelength of $\lambda=10.7$ μm. We demonstrate a spot size of $\lambda/4.3$ due to refraction of light outside the maximum angle of collection and total internal reflection at the lens surface. A model based on ray tracing is used to confirm the effect and show that spatial resolution is directly proportional to lens diameter and inversely proportional to the index of refraction for large emission and collection angles. Applications of refraction contrast imaging may include fluorescence microscopy, spectroscopy, and thermal imaging.

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