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# Scanner-Free and Wide-Field Endoscopic Imaging by Using a Single Multimode Optical Fiber

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**Short summary:** An endoscopic method is developed to replace the fiber bundle scope by a single multimode fiber. The dispersion in a multimode fiber is reversed by TLI methods. The speckle patterns are reduced by averaging the object images with different speckle illuminations.

## I. Optical fiber for Endoscopy

**Multimode optical fiber**
A multimode optical fiber has drawn interest because numerous independent spatial modes can be used for parallel information transport. However, the single multimode fiber could not be used in itself for the imaging purpose. When a light wave couples to and propagates through the fiber, the wave is distorted into a complex pattern because of mode dispersion.

**Mode dispersion**
Rays of light enter the fiber with different angles to the fiber axis, up to the fiber's acceptance angle. Rays that enter with a shallower angle travel by a more direct path, and arrive sooner than rays that enter at a steeper angle (which reflect many more times off the boundaries of the core as they travel the length of the fiber). The arrival of different components of the signal at different times distorts the shape.

Moreover, it has been much more challenging to use a single multimode fiber for practical endoscopic imaging in which the imaging operation should be performed in the reflection mode. In such a case, the light wave injected into the fiber is distorted twice, i.e., on the way in for the illumination and on the way out for the detection.

**Fiber scope**
For this reason, a fiber bundle has been widely used and thus became a standard for commercial endoscopes. In this fiber scope, each fiber constituting the bundle acts as a single pixel of an image, and the number of fibers in the bundle determines the pixel resolution.
Problem: Therefore, the requirement for a large number of fibers for high resolution imaging has posed constraints on the diameter of the endoscope, thereby causing considerable limitation on the accessibility of the device.

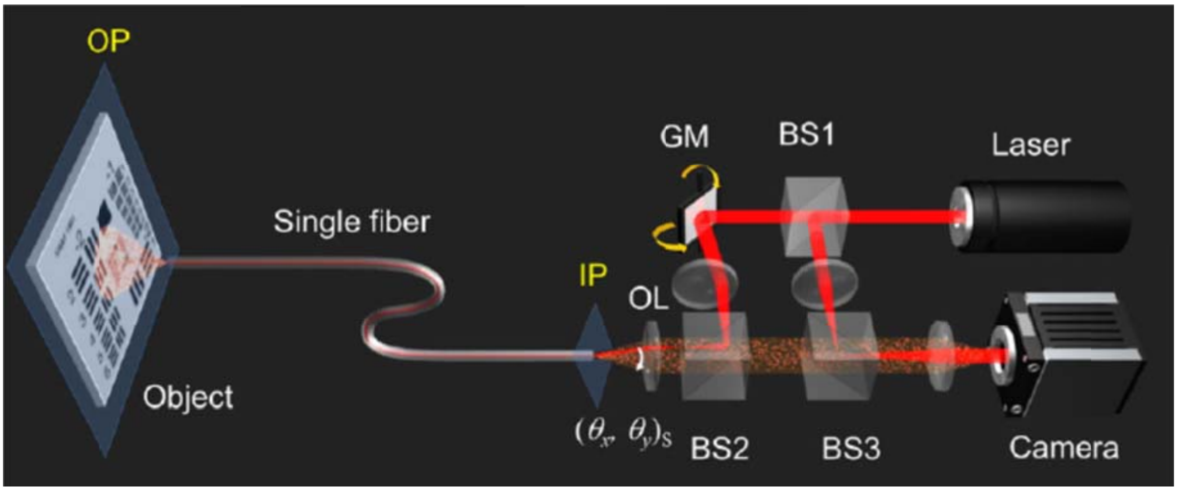
## II. PROPOSED LENSELESS MICROENDOSCOPY BY A SINGLE FIBER (LMSF)

The multimode fiber is converted into a self-contained 3D imaging device that does not require a scanner or a lens.

**Record the transmission matrix**
The authors make use of the measured transmission matrix of a multimode optical fiber to reverse the on-the-way-out distortion of the detected light.
The transmission matrix of an unknown complex medium was used for the delivery of an image through the medium. In fact, a multimode optical fiber can also be considered as a complex medium because bending and twisting of the fiber complicate wave propagation through the fiber.

**Speckle imaging method**
By employing the speckle imaging method, the on-the-way-in distortion was also eliminated.

## III. EXPERIMENTAL SET-UP




The beam illuminates at the input plane (IP) of the fiber, couples to the fiber, and subsequently propagates toward the object plane (OP) located at the exit of the fiber to illuminate a target object.
The laser beam reflected by BS1 is combined with the beam from the fiber to form an interference image at the camera. Using an off-axis digital holography algorithm, both amplitude and phase of the image from the fiber are retrieved.

## IV. TECHNIQUES FOR LMSF

**Two sources of the distortion**
Two processes mask the object information: (1) distortion of illumination light on the way in (IP to OP) and (2) the scrambling of the light reflected by the object on the way out (OP to IP). In

order to overcome these two distortions, they employ methods of speckle imaging and turbid lens imaging (TLI), respectively.

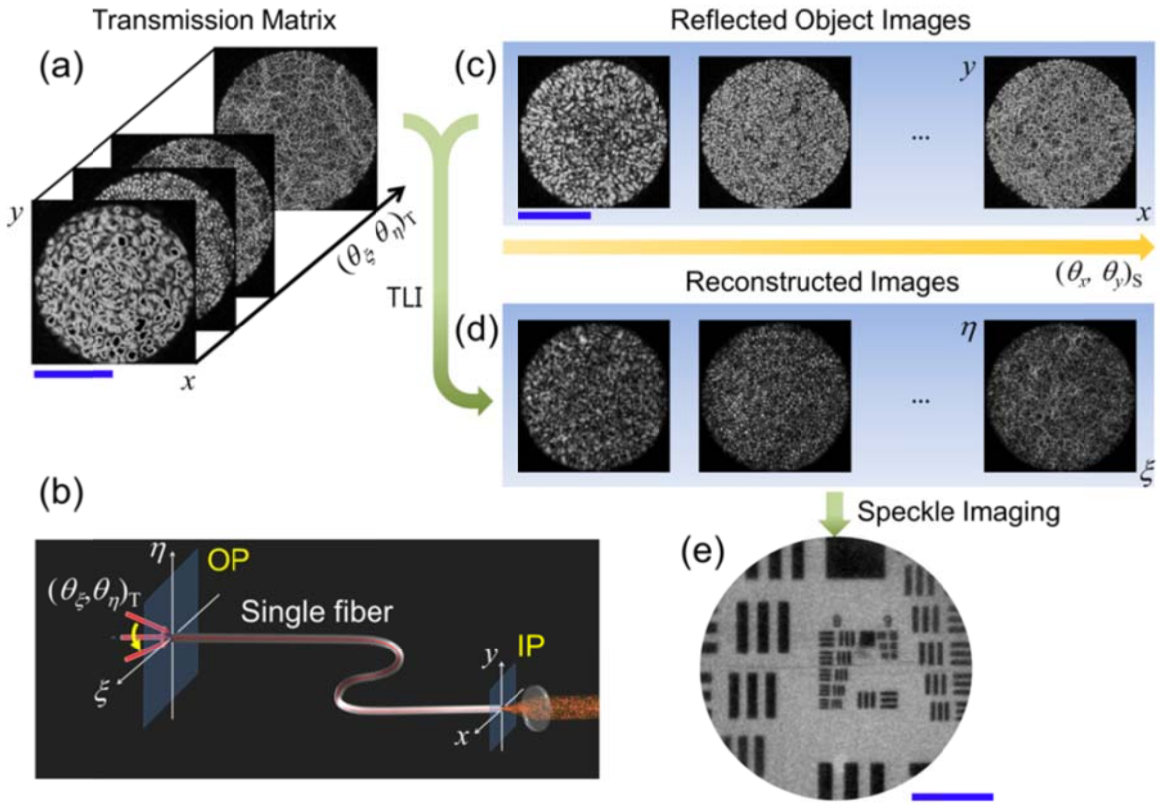
**Descrambling**

They first characterize the input-output response of the optical fiber from the object side to the camera side (OP to IP). They scan the incident wave in its angle $(\theta_\xi, \theta_\eta)_T$ to the fiber and record its transmitted image at the camera. A set of these angle-dependent transmission images is called the transmission matrix T. The transmission matrix elements are measured up to 0.22 NA by recording 15000 images.

Once the transmission matrix is recorded, an object image at the OP can be reconstructed from the distorted image recorded at the IP by using the TLI. The process is an inversion of the transmission matrix given by the relation EOP

$$E_{OP}(\xi,\eta) = T^{-1}E_{IP}(x,y)$$

Here EIP and $T^{-1}$ represent the recorded image at the IP and the inversion of the measured transmission matrix, respectively, and EOP is the image at the OP. Using Eq. (1), the distortion from OP to IP is reversed.




**Eliminating the speckle pattern**

The transmitted patterns are random speckles and the average size of the speckle decreases as the angle of illumination increases. This is because a high angle of illumination mostly couples to the high-order modes of the fiber.

The reconstructed images remain devoid of object structure because the illumination light is distorted due to the propagation of the illumination from IP to OP.
The change in the illumination angle causes the variation of the illumination light at the target object; in other words, a different speckle field is generated as we vary the angle $(\theta_x, \theta_y)_S$.
According to the speckle imaging method, a clean object image can be acquired if we average sufficient numbers of images recorded at different speckle illuminations.
The complex speckle illumination patterns are averaged out, leaving a clean object image.

**Scanning of the fiber end to enlarge the view field.**
They measured the transmission matrix of the fiber at an initial position of the fiber end and then used the same matrix to reconstruct object images taken while moving the fiber end.
Although bending induced by the movement of the fiber causes a change of the transmission matrix, many of the matrix elements stay intact and contribute to the image reconstruction.
According to their experiment, the LMSF is working well up to a centimeter-travel of the fiber end, confirming that LMSF has partial flexibility for searching for the view field.

## V. CONCLUSION

The same techniques used in turbid medium lens are employed to reverse the distortion of the multimode fiber.
The transmission matrix stays almost the same even with the centimeter changes of the fiber end.