Note: Folded optical system for narrow forward looking probe

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An optical system is described in which a laser beam makes three passes through a single graded index lens, forming a focus along the optic axis. It has important applications in endoscopic probes, where the forward looking characteristic permits the avoidance of obstacles and the narrow structure makes it minimally invasive. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4864149>]

There are many applications in which an optical probe is used to form an image of an inaccessible part. In medical applications¹ optical probes are used in endoscopes to obtain images within body cavities or tissues, and in industrial applications^{2,3} optical probes examine the interior of complex machinery. In many of these applications it is desirable for the probe to be as narrow as possible, for example, to be minimally invasive in a clinical environment.⁴ A single mode optical fiber is often used to transmit light to and from the head of the probe to maintain mechanical flexibility along with minimal light loss. In addition it is desirable for the probe to produce an image in the forward direction so that obstacles can be avoided as the probe is advanced. This note describes an optical arrangement that combines these sometimes conflicting objectives.

A typical arrangement for an optical probe is shown in Figure 1(a). Light from a single mode optical fiber is focused to a point by a graded index (GRIN) lens, and scanned to form an image by a vibrating mirror mounted on a Micro Electrical Mechanical System (MEMS) chip, not shown for clarity. The mirror may scan in two directions to produce a 2-dimensional image; alternatively it may scan in one direction and be coupled with an optical coherence tomography (OCT) system⁵ to obtain information along the direction of the optical path. Light reflected at the focus returns through the optical fiber for analysis outside the probe. The system works well but produces an image to the side, making positioning of the probe difficult.⁶

A second mirror may be added (Fig. 1(b)) to redirect the light to the forward direction.⁷ An added advantage is that the second mirror can be scanned in a direction orthogonal to that of the first mirror. However, the addition of the second mirror effectively doubles the width of the probe.

In the present arrangement, a mirrored surface is deposited directly on half of the exit end of a 2 mm diameter GRIN lens⁸ (Fig. 1(c)). Laser light at a wavelength of $1.3\ \mu\text{m}$ ⁹ enters the lens through a single mode optical fiber with a NA of 0.12. It reflects from the aluminized surface and passes back through the GRIN lens where it emerges as a parallel beam. The light then reflects from a 1 mm diameter stationary mirror, makes a third pass through the GRIN lens, and exits the probe through a cast resin¹⁰ window. The GRIN lens

focuses the light with a NA of 0.085 to a spot 1 mm from the exit window. This spot was imaged by a $10\times$ microscope objective on to a silicon CCD array. Although the sensitivity of silicon decreases strongly at wavelengths longer than $1.1\ \mu\text{m}$ the image clearly shows the size of the focused spot (Fig. 2).

Although half of the exit face of the GRIN lens is blocked by the aluminized surface the relatively short working distance from the lens permits obtaining NA's larger than those in the configurations shown in Figures 1(a) and 1(b). However, in OCT applications the optimal NA is a trade-off

FIG. 1. (a) Sideways looking probe based on a GRIN lens. (b) Forward looking probe using an additional mirror. The second mirror effectively doubles the width of the probe. For clarity the GRIN lenses in (a) and (b) have been shortened. (c) The present arrangement of a probe that is both forward looking and narrow.

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FIG. 2. Image of the focused spot produced by the probe in Figure 1 (c).

between high resolution and image depth, which is limited by the depth of field of the focused light. The present arrangement combines a small diameter probe with forward looking capability, and is easily tailored to a wide range of working distances and NA's.

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¹A. F. Fercher, W. Drexler, C. K. Hitzenberger, and T. Lasser, *Rep. Prog. Phys.* **66**, 239 (2003).

²T. Li, A. Wang, K. Murphy, and R. Claus, *Opt. Lett.* **20**, 785 (1995).

³S. R. Chinn and E. A. Swanson, in *2002 Handbook of Optical Coherence Tomography*, edited by G. J. Tearney and B. E. Bouma (Marcel Dekker, New York, 2002).

⁴B. J. Vakoc, D. Fukumura, R. K. Jain, and B. E. Bouma, *Nat. Rev. Cancer* **12**, 363 (2012).

⁵D. Huang, E. A. Swanson, C. P. Lin, J. S. Schuman, W. G. Stinson, W. Chang, M. R. Hee, T. Flotte, K. Gregory, and C. A. Puliafito, *Science* **254**, 1178 (1991).

⁶W. Jung, D. T. McCormick, J. Zhang, L. Wang, N. C. Tien, and Z. Chen, *Appl. Phys. Lett.* **88**, 163901 (2006).

⁷J. Wu, M. Conry, C. Gu, F. Wang, Z. Yaqoob, and C. Yang, *Opt. Lett.* **31**, 1265 (2006).

⁸This is a $\pi/4$ GRIN lens, in which rays follow a sinusoidal path of length $\pi/4$ radians. Model W20-S0250-120-NC NSG Group, 134 East Main Avenue SEPZ, Laguna Technopark, Binan, Laguna, Philippines 4024.

⁹Model LPS-1310-FC fiber pigtailed laser diode, Thor Labs, 435 Route 206, PO Box 366, Newton, NJ 07860-0366.

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