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Note: Design considerations and characterization of a flexible snapshot hyperspectral probe

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Hyperspectral imaging is a combination of imaging and spectroscopy to give detailed spectral information for each spatial point in the imaged scene. Using the concept of integral field spectroscopy, a custom fabricated two-dimensional to one-dimensional fiber bundle has recently been reported. It is used as a flexible snapshot hyperspectral probe, which can be used as an endoscope for biomedical applications. This paper reports on the design considerations of the fiber bundle as the flexible probe in the snapshot hyperspectral imaging system. The physical characterization of the custom fabricated fiber bundle and lateral resolution of the developed hyperspectral imaging system are also analyzed and described. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4978804>]

Hyperspectral imaging (HSI) combines imaging and spectroscopy to give detailed spectral signatures for each spatial point in the imaged scene.¹ Spectral information is acquired from hundreds of contiguous spectral bands to form a datacube, which is three-dimensional data in the spatial-spatial-spectral domain.^{2,3} The spectral information captured by HSI can be used to create a very detailed spectral library.⁴ In biomedical imaging, diseases which occur in sites, such as the gastrointestinal tract, are not easily accessible by conventional microscope or table-top setups. Therefore, probes and endoscopes are developed to satisfy the medical needs to image the human body from within. Probe-based HSI systems have been developed so that HSI can be performed within the body. These systems come in three major embodiments, using the spatial-scanning, spectral-scanning, and snapshot methods.^{5–7}

Snapshot hyperspectral (HS) imagers form a datacube from each captured image. Unlike the spatial- and spectral-scanning HS probes, the snapshot configuration does not require sequential scanning to form a datacube.⁸ Thus the snapshot HS imagers are preferred in real-time endoscopic applications as they have a faster image acquisition rate. This allows the movement of the probes to be controlled and *in vivo* tissue monitoring and disease diagnosis to be performed. In addition, the image quality becomes better as images are less susceptible to motion artifacts and pixel misregistration.⁹ However, the snapshot HS imagers usually compromise on the number of spatial point or spectral band as the amount of information in one image is limited.

Recently, a snapshot HS endoscope has been reported in a new configuration using integral field spectroscopy (IFS).¹⁰ It has a two-dimensional (2D) to one-dimensional (1D) fiber bundle where the fiberlets are arranged in 2D on the distal end and have been rearranged so that they form a row of fiberlets on the proximal end.¹⁰ This rearrangement of fiberlets reduces the

number of spatial dimension of the 2D image from two to only one at the proximal end, which is imaged by a spectrograph-based HS imager.¹¹

This paper details the design considerations of the 2D to 1D fiber bundle that is used in such a flexible snapshot HS endoscope. This fiber bundle serves two purposes of delivering light from its distal to proximal ends and carries out the concept of IFS through the rearrangement of fiberlets. At the same time, the fiber bundle has to be flexible and long with a small distal end so that it can enter the orifice of the body cavities for imaging. The physical characterizations of the custom fabricated fiber bundle are also reported. A United States Air Force (USAF) resolution chart is used to determine the lateral resolution of the endoscopic snapshot HSI system with the custom fabricated fiber bundle as the imaging probe.

The design considerations and specifications were determined by the authors and Polymicro Technologies™, who is the supplier of the selected fiberlets and also the manufacturer of the custom fabricated 2D to 1D fiber bundle. The custom designed fiber bundle serves as a prototype to prove the concept of using such a 2D to 1D fiber bundle with a spectrograph-based HSI system to form a snapshot HS endoscope. The main aspect to be considered for the integrated system is the imaging to capture the required information in a single scan to form the datacube.

The fiberlet to use depends on several factors. The first factor is the spectral range and it is ideal for the fiberlet to have high transmission in the operating spectral range of the HSI system, which is 400 nm–1000 nm.¹² This ensures that the effective spectral range of the integrated system is not compromised. The second factor is the relative size of the core and buffer of the fiberlet. The authors preferred a core size which is as large as possible relative to the cladding and buffer to allow more light from the sample to be captured by the fiberlet. It is also beneficial to have a smaller cladding and buffer to reduce the area in the sample image which always appears dark. Other factors to consider are the numerical aperture of the fiberlet and whether the buffer of the fiberlet can be removed

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before the assembly of the fiberlets to reduce the overall size of the fiberlet. The fiberlet chosen to fabricate the flexible 2D to 1D fiber bundle is FVP100110125 obtained from Molex. It has a relatively large core with a diameter of $100 \pm 3 \mu\text{m}$ compared to its buffer with a diameter of $124 \pm 3 \mu\text{m}$. It also has a high transmission in the spectral range of 180 nm–1150 nm, covering the operating spectral range of the HSI system.

The number of fiberlets to use for fabrication depends on the number of fiberlets at the 1D end of the fiber bundle that can fit into the line of view of the HSI system. The fiberlets were expected to be very close to each other when placed in a row at the 1D end of the fiber bundle. With the selected fiberlet having a buffer diameter of $124 \pm 3 \mu\text{m}$ and the line of view of the HSI system measured to be $\sim 12.5 \text{ mm}$, 100 of these fiberlets were to be used for fabrication. Therefore the length of the fiberlets at the 1D end, when placed in a row and close to each other, was expected to be $\sim 12.4 \text{ mm}$.

The 100 fiberlets at the 2D end of the fiber bundle would be arranged orderly in 10 rows of 10 fiberlets. They would be systematically arranged in the order in which they were arranged at the 1D end. The fiberlets at the 2D end can be arranged in a hexagonal or square array. The hexagonal arrangement was chosen as it has a larger packing ratio (lesser area proportion filled by empty space), even though the square arrangement can cover a larger area for imaging. The area covered by the fiberlets at the 2D is expected to be $\sim 1.09 \times 1.30 \text{ mm}^2$.

For the 2D to 1D fiber bundle to be used as an endoscope, the fiber bundle has to be long, thin, and flexible so that it can bend around the corners and be inserted into body cavities. The overall length of the fiber bundle was designed to be $\sim 1 \text{ m}$ with a minimum bend radius of $\sim 1 \text{ cm}$. A polyvinyl chloride jacket was also considered to run along the length of the fiber bundle to surround and protect the fiberlets. The jacket was designed to have a diameter of a few millimeters.

The fiberlets are to be held in place at the two ends of the fiber bundle using holders for mounting. Stainless steel was to be used to make the holders so that they are sufficiently strong to be mounted using opto-mechanical components. Since the 1D end of the fiber bundle is imaged by the HSI system and not used for probing, there is no size restriction on the holder at the 1D end. This holder was designed to be in a shape of a cuboid with an end-face area of $5 \times 20 \text{ mm}^2$ and a length of 60 mm. The 2D end of the fiber bundle is used for probing and therefore the size of its holder should be minimized. The fiberlets are to be encased in a cylindrical holder with a diameter and length of more than 4 mm and 30 mm, respectively.

The custom designed 2D to 1D fiber bundle fabricated by Polymicro Technologies™ is shown in Fig. 1(a). Most of the specifications of the fiber bundle are close to the initial design specifications. The fiber bundle has an overall length of 1.05 m and is covered by a 0.93-m long polyvinyl chloride jacket of 3.5 mm diameter. The sheaths located near the two ends of the fiber bundle have a diameter and length of 4.2 mm and 30 mm, respectively.

The holders at the two ends were made using stainless steel. The holder at the 1D end of the fiber bundle is shown in Fig. 1(b). It is cuboid in shape and has an end-face area of $5 \times 20 \text{ mm}^2$ and length of 30 mm. Although the length is only half of what was initially designed, this reduction in length is

FIG. 1. (a) 2D to 1D fiber bundle placed near a 23-mm diameter coin and holders at (b) 1D and (c) 2D ends of fiber bundle.

actually preferred as it makes the 1D end of the fiber bundle smaller. The holder at the 2D end of the fiber bundle is shown in Fig. 1(c) with a diameter of 5 mm and length of 30 mm. This holder is the component with the biggest dimension in the distal end of the fiber bundle, but it can be used as an endoscope to access regions in the body, such as the pharynx.

100 fiberlets (FVP100110125, Molex) were used in the fiber bundle. At the 1D end of the fiber bundle, the fiberlets are arranged in a row and kept close to each other. The row of fiberlets has a measured length of $\sim 12.2 \text{ mm}$. The fiberlets were numbered accordingly from the left [Fig. 2(a)]. At the 2D end, the fiberlets are arranged in a sequence across the column towards the right and then down the row to form 10 rows of 10 fiberlets in a hexagonal array [Figs. 2(b) and 2(c)]. The fiberlets here occupy an area of $\sim 1.11 \times 1.32 \text{ mm}^2$. The white diamond in Fig. 2(c) indicates the position of Fiberlet 4 which was inactive and thus appeared to be dark. The packing ratio of the fiberlets' cores on the 2D end-face is $\sim 55\%$.

The experimental setup was as previously reported,¹⁰ except that the broadband light source (MI-150, Edmund Optics) was placed before the USAF chart for transmittance imaging to determine the lateral resolution of the system. The USAF chart was placed at $\sim 0.5 \text{ mm}$ away from the 2D end-face of the fiber bundle. The system had an exposure time of 0.1 s and frame rate of $\sim 6.16 \text{ Hz}$.

FIG. 2. Front views of holders at (a) 1D and (b) 2D ends of fiber bundle and (c) close-up view of fiberlets at 2D end of fiber bundle. Numbers indicate numbering order of fiberlets.