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Multi-pixel X-ray detection integrated at the end of a narrow multicore fiber

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We introduce and demonstrate the concept of a multi-pixel detector integrated at the tip of an individual multicore fiber. A pixel consists here of an aluminum-coated polymer microtip incorporating a scintillating powder. Upon irradiation, the luminescence released by the scintillators is efficiently transferred into the fiber cores owing to the specifically elongated metal-coated tips which ensure efficient luminescence matching to the fiber modes. Each pixel being selectively coupled to one of the cores of the multicore optical fiber, the resulting fiber-integrated X-ray detection process is totally free from inter-pixel cross-talk. Our approach holds promise of fiber-integrated probes and cameras for remote X- and Gamma-ray analysis and imaging in hard-to-reach environments. © 2022 Optica Publishing Group

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The need for novel tools able to detect ionizing radiations within tiny recesses and/or extreme environments (of high pressure, temperature or radioactivity) is seen to rapidly grow in many scientific, medical and industrial domains. Being compact, robust and flexible, optical fibers are widely considered as a promising optical tool for addressing this demand, as they allow a direct control on light encoded information collected from hard-to-reach locations.

Fiber probes based on the integration of a scintillating element onto the tip of the optical fiber have been widely explored for the local and real-time dosimetry of ionizing radiations. Given their inert, passive, and possibly biocompatible nature, such devices are particularly appealing in a variety of applications and techniques ranging from in-vivo dosimetry in cancer therapies to *in situ* dosimetry within harsh environments such as a nuclear reactor [1–8].

Most of these studies have been realized with single pixel detectors obtained by coupling a scintillating cell to an individual fiber. Bringing multi-pixel X-ray detectors within hard-to-reach environments would enable new opportunities in radiation analysis, opening the prospect of *in vivo* or *in situ* real-time imaging.

However, integrating a pixel array in a compact fiber-integrated architecture remains a challenge. Optical fibers being typically larger than 90 μm , the parallel implementation of a single pixel fiber probe in a fiber bundle represents limits in terms of compactness and image sampling [9].

Compactness and resolution issues can be alleviated by implementing multiple pixels onto the same optical fiber. Therriault et al. developed a three-pixel detector integrated at the end of an individual fiber [10]. The multi-pixel probe was sufficiently compact to be inserted within a catheter for brachytherapy applications [11, 12]. However, since the luminescence spectra of the three different scintillators used as detection pixels noticeably overlap, the detector suffers from inter-pixel cross-talk. The development of an array of detection pixels at the tip of an individual optical fiber has so far never been reported.

In this paper, we demonstrate a seven-pixel X-ray detector engineered at the tip of an individual fiber. Our detector is achieved by coupling seven metal-coated scintillating micro-tips to a multicore fiber, each microtip being coupled to one of the fiber cores. The resulting seven parallel detection channels are shown to be totally independent from each other, thus holding promise for a high contrast real-time imaging in hard-to-reach environment. Demonstration is realized both with monochromatic and polychromatic X-rays. Multicore fibers have recently demonstrated new prospects for sensing applications [13, 14] and lab-on-fiber technology [15, 16]. We here extend the multicore-fiber-based technology to the analysis and imaging from ionizing radiations.

Our fiber-integrated multipixel detection system is fabricated using a photopolymerization process at one endface of a multicore fiber from Fibercore (Model SM-7C1500). The optical fiber shows seven 6.3- μm -diameter cores arranged in a hexagonal lattice, with an inter-core spacing of 35 μm . The photopolymerization involves a scintillating photopolymer locally exposed with a laser light travelling through the fiber. One fiber endface is immersed with the polymer/scintillator mixture while an expanded laser beam ($\lambda=521$ nm, laser diode from Thorlabs) is projected onto the other end to homogeneously illuminate all the cores of the fiber. The so-excited seven parallel

64 fiber modes carry almost the same power, thereby similarly trig-
 65 gering polymer hardening at the core outputs. The total laser
 66 power at the fiber output and exposure time are $0.7 \mu\text{W}$ and 4
 67 seconds, respectively. After fiber rinsing with ethanol, seven
 68 scintillating microtips arranged in a hexagonal lattice appear
 69 at the fiber output face. Being realized from the fiber modes
 70 themselves at a wavelength closely approaching that of the scin-
 71 tillator luminescence, the so-produced elongated scintillating
 72 microtips are expected to reciprocally efficiently transfer their
 73 X-ray excited luminescence into the fiber. To increase probe effi-
 74 ciency, the multipixel detection array can be metal coated to limit
 75 the luminescence leaving the microtips outside the fiber. Metal
 76 coating involves here the deposition of a few-nanometer-thick
 77 titanium adhesion layer followed by a 125-nm thick aluminum
 78 layer. Aluminum is chosen for its high reflectivity at visible
 79 wavelengths and high transparency to X-rays.

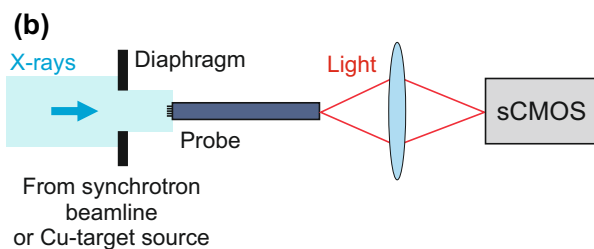
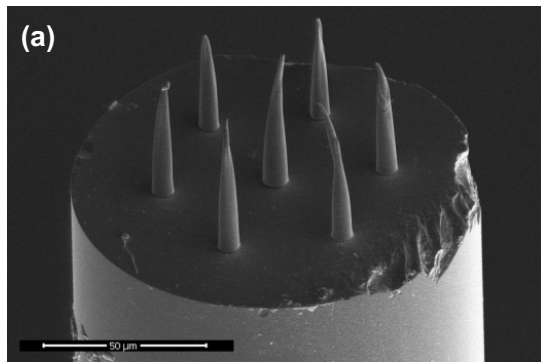


Fig. 1. (a) SEM image of a fiber-integrated multi-pixel detection array on top of a seven-core optical fiber. Each pixel is in direct optical coupling with one of the fiber core. (b) Scheme of the experimental set-up for the detector demonstration.

80 To produce the scintillating photopolymer, we first grind
 81 a commercial $\text{Gd}_2\text{O}_2\text{S}:\text{Eu}$ powder (Phosphor Technology,
 82 Ref.UKL63/UF-R1) in a mortar with a pestle. The ground powder
 83 is then mixed with ethanol to be filtered with a cellulose
 84 acetate membrane whose pore diameter is of $1.2 \mu\text{m}$. Finally, the
 85 filtrate is dried to form a superfine powder. Next, the scintil-
 86 lating material is mixed with a photosensitive polymer, which
 87 combines an eosin Y (tetrabromofluorescein) used as a sensi-
 88 tizer dye, an co-initiator (MDEA: N-methyldiethanola-mine)
 89 and a multifunctional acrylate monomer, pentaerytritoltriacy-
 90 late (PETIA) [17]. This photosensitive emulsion provides robust
 91 microstructures at the endface of an optical fiber [18–21]. A
 92 weight ratio of 1:5.2 between the photopolymer and the scintil-
 93 lating powder ensures a high concentration of scintillator within
 94 the mixture. $\text{Gd}_2\text{O}_2\text{S}:\text{Eu}$ shows excellent yield, linearity and
 95 stability upon exposure [21, 22]. This scintillator also show sub-
 96 millisecond decay and low afterglow upon exposure at energies
 97 of the order of a few keV, thereby leading to a response time that

is fast enough for numerous applications. Faster luminescence
 may however be achieved with $\text{Gd}_2\text{O}_2\text{S}:\text{Tb}$ material [6, 23, 24].

Figure 1(a) displays a scanning electron micrograph of a re-
 sulting fiber-integrated multipixel detector. The pixel array takes
 the form of seven aluminum-coated scintillating micro-tips of
 similar geometries located on top of the seven fiber cores.

The microfabricated detector is demonstrated at the Metrology
 beamline of the synchrotron Soleil. The experimental set-up
 is depicted in Fig. 1(b). A monochromatic 12-keV radiation is
 projected onto the microstructured facet of the fiber (the beam
 and fiber axes are aligned). At 12 keV, a flux of $2.1 \cdot 10^9$ photons/s
 is measured across the $1 \times 1 \text{mm}^2$ radiation field. An adjustable
 diaphragm is positioned in front of the fiber, to control the beam
 width. The diaphragm and fiber detector are positioned on two
 independent 3D motorized stages. The bare output face of the
 fiber is imaged with a standard sCMOS camera (Zyla model
 from Andor Technology) equipped with a ($\times 10, 0.3$) microscope
 objective (Olympus). The camera is positioned outside the irradi-
 ation zone of the primary beam. We verified that negligible stem
 effect (i.e., Cerenkov effect) [25, 26] is generated by the fiber
 itself upon exposure: no signal is detected when a bare scintillator-free
 multicore fiber is placed within the above-described test-bed.
 The camera is used as a photometer array to simultaneously
 read the seven instant optical signals delivered in parallel by
 the fiber-integrated multipixel platform. The readout signals are
 obtained by integrating image intensity over 64×64 -pixel regions
 of interest (ROI) tightly enclosing the seven output light spots
 (one ROI per spot). Images are recorded at a rate of 10 Hz.

Figure 2(a) shows an image of the output endface of the multi-
 core fiber. The observed seven light spots originate from the scin-
 tillation light generated upon irradiation by the fiber-integrated
 pixel array and guided through the fiber to the camera. These
 light spots are well separated in the image, thereby avoiding arti-
 factual inter-pixel crosstalk in the optical readout process. Since
 a relatively homogeneous distribution of light spots is imaged
 by the camera (see Fig. 2(b)), we conclude that the concentration
 of scintillators across the microtip array is almost constant and
 the fabrication process satisfies pixel homogeneity. Only one
 pixel shows a signal level deviating from the others's. Note that
 correction factors can be applied to the pixel array to correct
 little signal offsets.

The response of our fiber-integrated multipixel detector in
 terms of dose linearity and repeatability is reported in Fig. 3.
 The measurement repeatability (Fig. 3(a)) is determined over
 ten exposures of ten seconds each. For the ten exposures at a
 near-constant radiation flux, the light intensities accumulated
 by each detection pixel show standard deviation from signal
 average spanning from 0.4 % and 1.29 %. Note that these er-
 rors are mainly due to slight variations of the X-ray intensity
 at the synchrotron beamline. The X-ray flux in a synchrotron
 is known to be a decaying function of time due to the lifetime
 limitations of the electrons within the storage ring. To overcome
 the problem, electrons are periodically injected into the storage
 ring to compensate beam losses and keep a constant photon flux
 at beamlines (cf. "top-up" operation). Since our measurements
 are realized between two successive "top-up", we numerically
 compensated the X-ray intensity decay in our data acquisition
 from a linear regression calculation. A linear regression being a
 first approximation of the real time-varying decay of the X-ray
 beam, residual intensity fluctuations are preserved and explain
 the harmonic fluctuations of the data points visible in Fig. 3(a).
 Therefore the offsets to the perfect repeatability imputed to our
 detection system are smaller than the values given in the figure

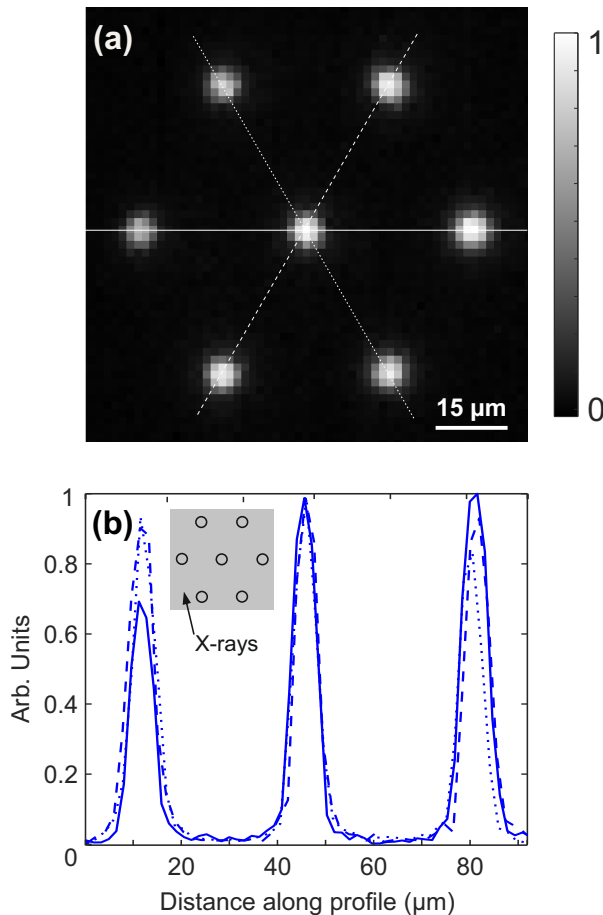


Fig. 2. (a) Optical image of the fiber output face when the pixel array is exposed to a $1 \times 1 \text{ mm}^2$ radiation field (see inset of (b)). (b) Intensity plots along the three white lines of (a).

inset. The linearity of the detector with regards to the deposited dose is assessed by accumulating the signals detected by each of its fiber-integrated pixel over 1, 3, 5, 10, 15, 20, 25, 30, 35 and 40 seconds of irradiation at a near-constant flux (see Fig. 3(b)). The linearity factor R across the pixel array exceeds 0.999.

To evidence potential spurious inter-pixel cross-talk in the overall detection process, the X-ray radiation is narrowed until exposing only one of the seven pixels of the fiber probe. To this end, the diaphragm diameter is decreased down to $35 \mu\text{m}$ and the resulting pinhole is centered with respect to a single pixel at the fiber detector. Fig. 4(a) reports an optical image of the output endface of the fiber when the tight X-ray pencil selectively irradiate the pixel at the center of the detection array. We see that only the exposed pixel delivers light to the camera via the multicore fiber, the neighboring detection channels remain unexcited. This is confirmed on the intensity plots of Fig. 4(b). Outside the fiber core coupled to the pixel under exposure, the detected intensity is at the level of the dark signal of the camera: inter-pixel cross-talk is therefore negligible.

Our fiber detector can operate under polychromatic X-ray radiations as well. This has been verified by testing the fiber system with a polychromatic radiation from a Cu-target source (20 kV, 40 μA / Bruker D8 DISCOVERY diffractometer). Figure 5 shows time traces simultaneously delivered by the seven pixels of the fiber probe upon exposure. At the beginning and at the end of the acquisition, the source shutter is closed to verify

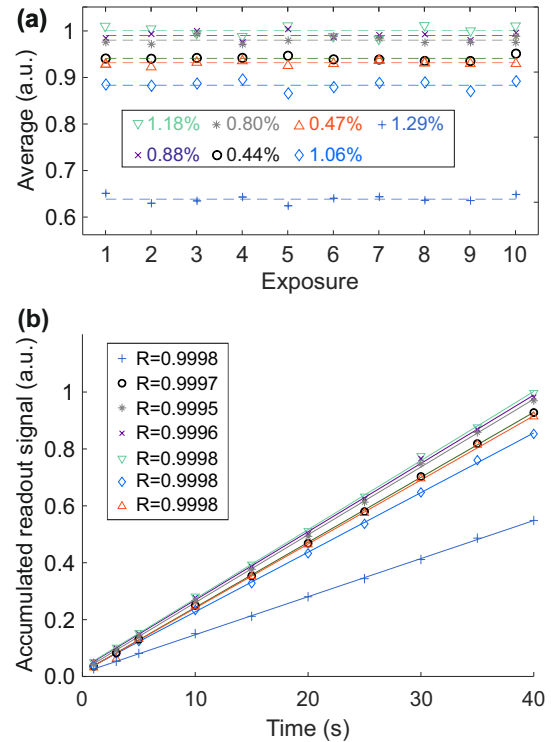


Fig. 3. (a) Repeatability of the multipixel detection system over ten successive exposures. (b) Linearity of the detector versus the exposure duration (i.e., accumulated dose).

that no spurious residual light (such as in-fiber coupled room light or scintillator afterglow) is detected by the system. We see that without X-rays, the afterglow generally observed with Eu-doped gadolinium oxysulfide [22] is here negligible. When the shutter is open (during 110 seconds), seven signals are simultaneously detected with a signal-to-noise ratio ranging from 30 to 42. Note that the signal-to-noise ratio can be enhanced by finding an optimum combination between tip shape and scintillator concentration within the photopolymer. All the above-studied detection properties and performances are also verified with this polychromatic source.

To conclude, we introduce the concept of a multi-pixel X-ray detector integrated at one endface of an individual multicore fiber. A seven-pixel array is demonstrated onto a narrow $125\text{-}\mu\text{m}$ diameter seven-core fiber, each pixel being engineered simultaneously on top of each fiber core by photolithography. The resulting imaging system shows good repeatability and linearity regarding the accumulated radiation dose and it is totally free from inter-pixel crosstalk. Such a fiber detector could be used to perform multi-point analysis of X-ray microbeams. This multipoint detection unit could also be seen as a building block of future ultracompact camera engineered from a bundle of multicore fibers. Being compact and flexible, such fiber camera systems would enable *in situ* or *in vivo* high resolution imaging in hard-to-reach locations. By leveraging the ubiquity of fiber-optics technology, this may represent new prospects in a broad range of scientific, medical, and industrial applications.

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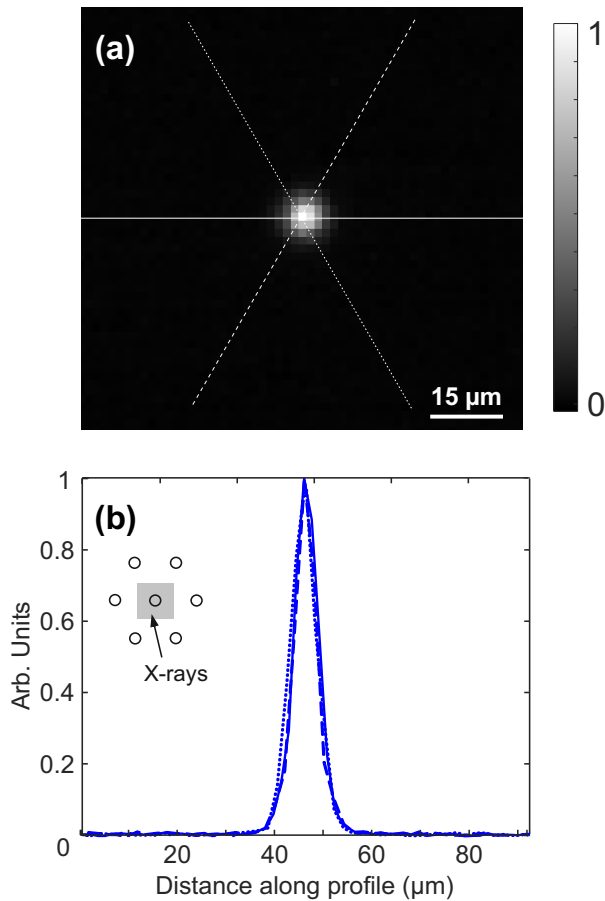


Fig. 4. (a) Optical image of the fiber output face when the pixel array is exposed to a $35 \times 35 \mu\text{m}^2$ radiation field centered with respect to the center pixel (see inset of (b)). (b) Intensity plots along the three white lines of (a).

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222 **Disclosures.** The authors declare no conflicts of interest.

223 **Data availability.** Data underlying the results presented in this
224 paper are not publicly available at this time but may be obtained from
225 the authors upon reasonable request.

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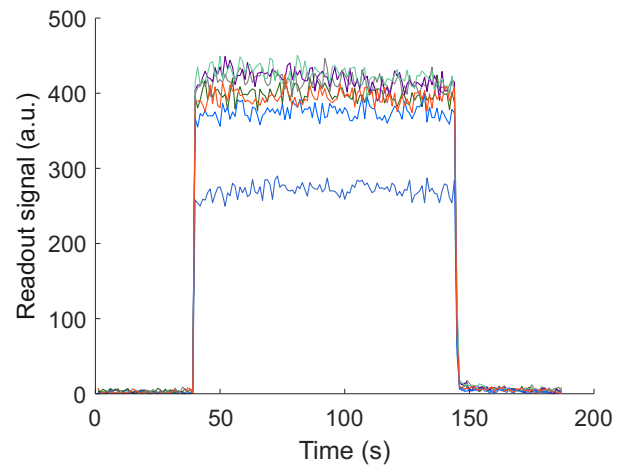


Fig. 5. Readout signal from the seven detection pixels upon a 110 s exposure to polychromatic X-rays from a Cu-target source. During the first and last 40 s of the acquisition, the source shutter is closed to assess the background (dark) signal of the system. When the radiation is activated, the SNR ranges from 30 and 42.

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