# Flexible Liquid-Filled Scintillating Fibers for X-Ray Detection

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***Abstract*—We present the design and fabrication of flexible, liquid-filled scintillating fibers for X-ray detection made from silica fibers and silica capillaries. The scintillating fibers were characterized using ultraviolet light exposure and we also performed an experiment demonstrating X-ray detection.**

***Keywords*—liquid-filled fibers; scintillating fibers; X-ray detection**

## I. Introduction

Due to the inherent inflexibility of the digital electronics and scintillating materials used both in charge integrating and photon counting architectures, shapes with complex geometries cannot be imaged accurately. This is particularly problematic in industrial non-destructive testing, where defects in complex shapes are difficult to detect [1], and in medical applications, where the inability to resolve features within the human body is offset by higher radiation dosage.

Here we present the design and fabrication of flexible liquid-filled scintillating silica fibers. The work is ongoing, at the time of writing, and part of the FleX-Ray project [2], [3], whose objective is to create a flexible digital X-ray detector that enables high-resolution images of curved objects, and that can self-report its shape. A web of scintillating fibers will be used to detect the X-rays and guide the scintillation light to silicon photomultipliers as sketched on Fig. 1. Liquid-filled fibers and plastic scintillating fibers (PSF) can both be used in the detector, but for this specific application, the use of liquid-filled silica fibers and capillaries have several benefits compared to their plastic counterparts. Liquid-filled fibers provide freedom to select scintillator and can be filled with different types of scintillating cocktails, e.g., high-Z loaded liquids. This is important for optimizing the detection parameters such as X-ray attenuation, photon yield, and scintillation time. The diameters of the capillaries can be smaller than for PSFs and can be adapted to obtain the desired resolution. In addition, it has been shown that the liquid filled fibers have potentially higher resistance to radiation damage than PSFs [4]. They can also be fusion-spliced or connected by standard mechanical couplings to conventional multimode fibers, thereby reducing overall optical losses.

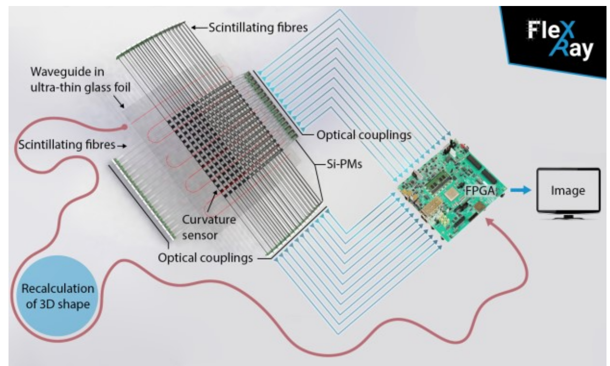


Fig. 1. A concept overview of the fiber-based, flexible, shape self-reporting X-ray detector.

## II. Liquid-filled Scintillating fibers

Leveraging expertise gathered from previous projects and optofluidic arrangements at RISE [5]–[7], several design concepts based on liquid-filled capillaries/hollow fibers were manufactured and tested, with fiber diameters from 125 µm to 350 µm. The selected design for the all-silica fiber component, is shown in Fig. 2. It consists of three different parts. The central, liquid-filled, active part of the component is a capillary with an internal diameter of 50 µm. At each end of this part there is a short piece of a capillary with an 8-µm inner diameter that is partially filled with liquid, and at the other end of these capillaries, multimode (MM) fibers are connected to lead the light to the detectors. The purpose of the 8-µm capillary is to reduce the light scattering of the air-liquid interface. The entire assembly is coated with a low-index

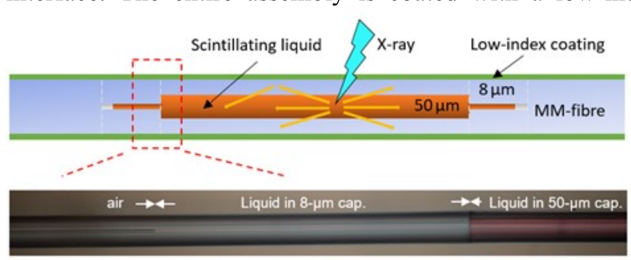


Fig. 2 Top: Design for the FleX-RAY scintillating fiber. Bottom: Microscope image of a component of the same design, filled with a red dye for visibility.

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polymer (OF-133-V3, MY Polymers Ltd) to allow for light to be guided not only in the liquid and the core but in the entire cross-section of the silica glass. This improves the trapping efficiency and reduces the optical losses. The outer diameter of the glass fibers and capillaries was 125 µm.

A simulation program based on GEANT4 [8] was used to estimate key parameters (Table 1) and to aid the design process. Simulation results for the liquid filled fiber along with data from the technical specifications for a PSF are presented in Table I. The simulation indicates an improvement of a factor of two compared to the PSF in terms of captured photons per unit time. The high trapping efficiency, 6%, is a result of applying the low index coating on the component, which increases the acceptance angle and acts as a cladding. Hence, the proposed components offer a potential performance improvement while, at the same time, also being more versatile and enabling higher spatial resolution.

TABLE I. PARAMETERS FOR THE SCINTILLATING FIBER

| ***Parameters*** | ***RISE Liquid-filled fiber*** | ***PSF (BCF-10), Saint-Gobain*** |
|---|---|---|
| Conversion eff. (photons/MeV) | 14 000 | 8000 |
| Scintillation time | 2.5 ns | 2.7 ns |
| Light trapping | 6.1 % | 5.6% |
| Captured photon per unit time (photons/MeV/ns) | 342 | 166 |
| Sensing diameter | 50 µm | >500µm |

## III. FABRICATION METHOD

The fabrication process of this scintillating fiber is outlined in Fig. 3. First the central capillary, typically 20 cm in length is fusion spliced at both ends to 2-cm pieces of capillaries with 8 µm inner diameter. If these splices are well done (see Fig. 4a) the component can be filled within a few hours by capillary forces without applying pressure. The component can be filled more quickly if a pressure is applied, i.e., using a pressurized vial as shown in Fig. 4b. After the filling, the component is capped by fusion splicing the MM fibers to the open ends of the 8-µm capillaries. With the splice recipe used, the liquid-air interface in the capillary needed to be at least 4 mm away from the splice point to avoid overheating the liquid, which results in soot deposits in the capillary. After the splicing, the component is completed by recoating the stripped sections with the low-index polymer.

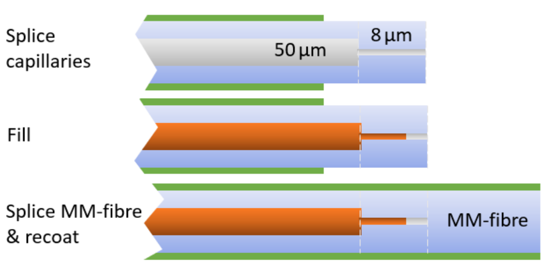


Fig. 3. Procedure for the fabrication of our proposed liquid-filled scintillating fiber.

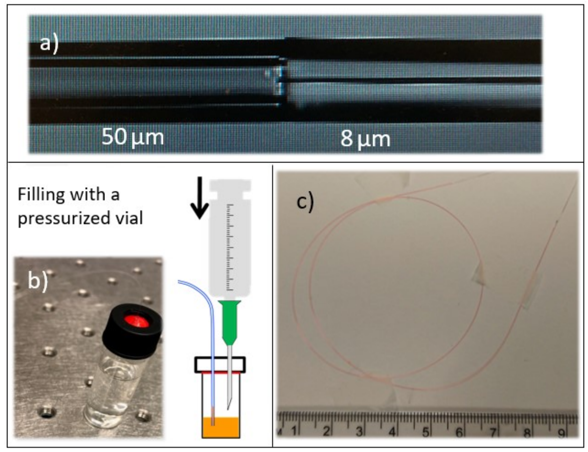


Fig. 4. a) A splice between capillaries with 50 µm and 8 µm inner diameters. b) Filling of a component using a pressurized vial; c) a completed component filled with a red dye.

The capillaries and a custom-made MM fiber were both fabricated by RISE using their fiber drawing facilities. The low-index coating material, and an overcoat of standard acrylate, were also applied in the drawing process.

## IV. TEST AND VERIFICATION

### *A. UV illumination test and bend radius test*

The fabricated scintillating components were first tested using ultraviolet exposure. This test provides a relative measure of the component performance. The experimental arrangement used is shown in Fig. 5. An LED, emitting at 275 nm (40 nm FWHM), was used to pump the scintillating fiber from the side and the generated light (peak wavelength of 430 nm) was guided to a spectrometer (QE65000, Ocean Optics). Examples of spectra resulting from exposure at different positions along a scintillating component are shown in Fig. 6.

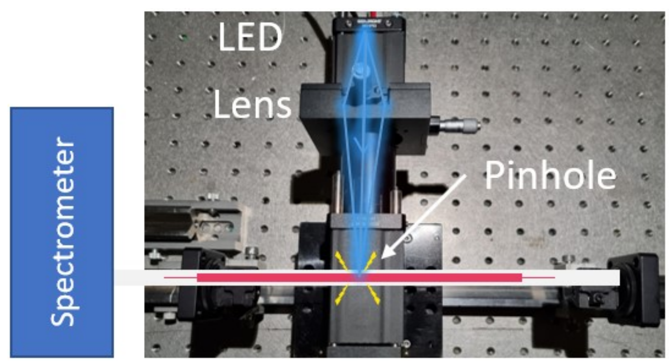


Fig. 5. Arrangement for ultraviolet exposure of the liquid-filled scintillating fibers.

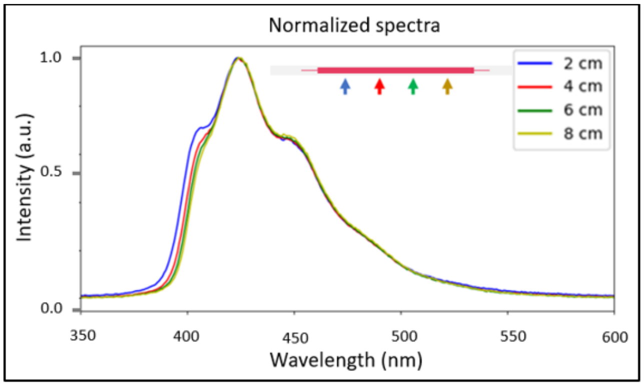

Fig. 6. Measured generated light at different exposure positons along the active fiber.

Bending loss is a critical parameter for our scintillating fibers, and it was tested using the arrangement shown in Fig. 7. Light from a 430-nm LED source, with a similar emission spectrum to the scintillating liquid, was launched into the component and the transmitted intensity was measured. The active part of the component was bent to different radii from 10 cm to 1 cm. No measurable change could be detected in the three components that were tested.

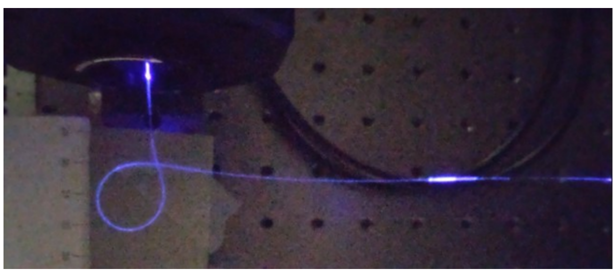
Fig. 7. Test of bending losses of a scintillating liquid-filled fiber.

*B. X-ray test*

A comparative measurement between a PSF (SCSF-78, Kuraray) and RISE's scintillating fiber, filled with a liquid scintillator (BC505, Saint-Gobain), was performed. The scintillation spectrum was measured at one end of the fiber during exposure to X-rays (Excillum MetalJet D2 source, 24-keV line emission, and 70 kV acceleration voltage). The exposed section of the fibers was 20 cm, and equal for both types.

To simplify the comparison, the spectrometer reading was divided by the cross-sectional area of the active parts of the two fibers and then normalized to the maximum value for the liquid-filled component. The result indicates three times more scintillation light at the detector per cross-sectional area for the liquid-filled fiber compared to the PSF. Simulations in GEANT4 predict the improvement to be 1.5, due to differences in X-ray stopping power and the light yield of the scintillators. The remaining difference could be explained by improved trapping efficiency and reduced optical attenuation, but further tests are needed to confirm this.

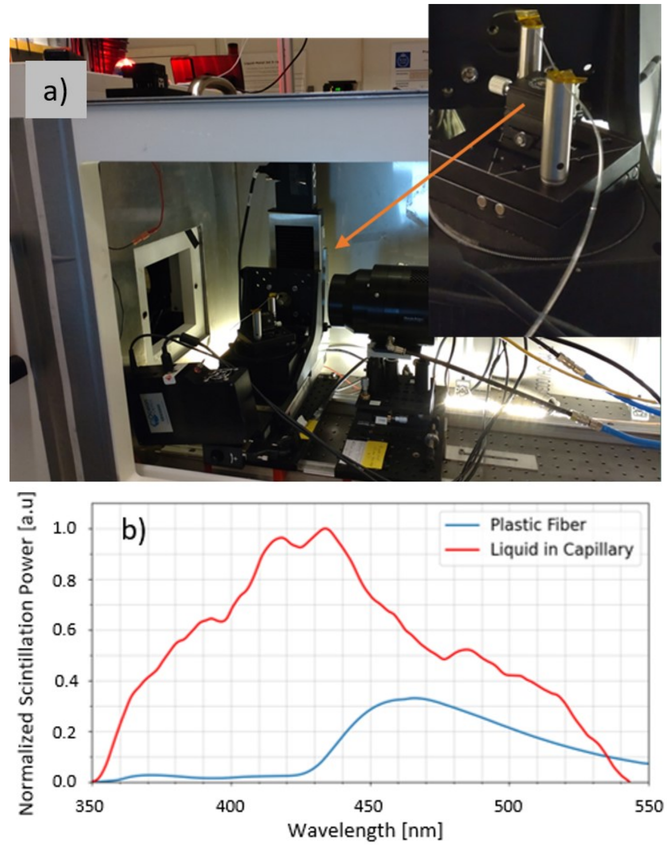

Fig. 8. a) Experimental arrangement for X-ray exposure. b) Comparison of the low pass filtered scintillation spectrum from a liquid filled fiber component and a plastic scintillating fiber (PSF).

## V. FUTURE WORK

Additional X-ray tests will be made on more components to verify the performance of the scintillating fiber components. It is also planned to fabricate a small-scale flexible X-ray detector using the liquid-filled fibers, and to perform imaging experiments using that demonstrator.

## ACKNOWLEDGMENT

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