Published in final edited form as:

Opt Lett. 2016 May 01; 41(9): 1973–1976. doi:10.1364/OL.41.001973.

Lensless, ultra wideband fiber optic rotary joint for biomedical applications

Wihan Kim¹, Xi Chen¹, Javier A. Jo¹, Brian E. Applegate^{1,*}

¹Department of Biomedical Engineering, Texas A&M University, 101 Bizzell St., College Station, TX 77843

Abstract

The demands of optical fiber based biomedical applications can in many cases outstrip the capabilities of lens based commercially available fiber optic rotary joints. In some circumstances it is necessary to, use very broad spectral bandwidths (near UV to short-wave IR), specialized optical fibers such as double clad fiber, and have the capacity to accommodate high rotational velocities. The broad spectrum, stretching down into the UV presents two problems, adequate chromatic correction in the lenses across the entire bandwidth and strong UV absorption by the fluids used to lubricate the rotary joint. In order to accommodate these types of applications, we have developed an ultra wideband lensless fiber optic rotary joint based on the principle that when two optical fibers are coaligned and placed in contact (or very close) the optical losses at the junction are very low. The advances demonstrated here enable excellent performance (<0.2 dB insertion loss) even down into the UV and spanning a wavelength range of at least 355–1360 nm with single mode, multimode, and double clad fibers. We also demonstrate excellent performance, ~0.38 dB insertion loss, at rotational velocities up to 8800 rpm (146 Hz). To the best of our knowledge this is the first demonstration of this type of rotary joint capable of such a wide bandwidth and high rotational velocities.

OCIS codes:

(060.2330) Fiber optics communications;; (060.2360) Fiber Optics links and subsystems;; (060.2430) Fibers, single-mode.

Fiber optic rotary joints (FORJ) are widely used for transmitting optical signals where one side of a fiber junction must be freely rotating. Numerous fields take advantage of these devices, e.g. light communication through robotic joints, radar antenna based on slip-ring housings for satellite communication systems, military radar and civil radar [1–3]. In particular, we are motivated by applications in medical imaging and sensing where it is sometimes necessary to use very broad spectral bandwidths, near UV to short-wave IR, [4] as well as more specialized optical fibers such as double clad fiber [5]. These conditions are very challenging for the current set of commercially available FORJ that use lenses in their optical design. The broad spectral bandwidth requires management of chromatic aberration in the lenses critical thus making it difficult and potentially very expensive to design and

*Corresponding author: apple@tamu.edu.

construct high performance lens based FORJ. Likewise, good performance at short wavelengths requires a judicious choice of lubricants, since many typical lubricants have strong UV absorption that can lead to degradation of the lubricant, thermal damage to the optics, and unwanted background fluorescence. Specialized fibers, such as double clad fiber, pose additional challenges, e.g. maintaining the modal integrity of the light as it passes through the rotary junction and accommodating the different numerical apertures of the single mode and multimode cores.

In particular, we are interested in developing technologies for intravascular optical imaging in arteries using catheter endoscopes. This is most frequently accomplished by rotating the endoscope at high-speed while pulling the endoscope back. This creates a spiral image of the artery. The artery must be flushed with a transparent fluid during imaging in order to clear the blood. This introduces an additional challenge peculiar to our application, short bursts of rapid rotation of the FORJ at velocities exceeding 6000 rpm for a time duration of 4–6 s. The high rotational velocity is required due to the maximum volume/time allowed for the flush to ensure patient safety. This is in fact how commercial intravascular optical coherence tomography (OCT) systems function. We have been working toward developing multimodal systems [6] integrating OCT with Fluorescence Lifetime Imaging Microscopy (FLIM) [7] in order to characterize atherosclerotic plaques [8, 9] and garner information that has previously only been available in postmortem histopathology. Extending this multimodal approach to intravascular imaging invokes all of the requirements enumerated above for the FORJ, i.e. extremely broad bandwidth, high rotational velocity, and maintenance of modal integrity with a double clad fiber.

Building upon the work of Li and coworkers [4, 10] we have developed a lensless fiber optic rotary joint based on the principle that when two optical fibers are coaligned and placed in contact (or very close) the optical losses at the junction are very low. The advances demonstrated here enable excellent performance even down into the UV and spanning a wavelength range of at least 355–1360 nm with single mode, multimode, and dual clad fibers. We also demonstrate excellent performance at rotational velocities up to 8800 rpm. The primary components of the lensless ultra wideband fiber optic rotary joint (UFORJ) are shown in Figure 1.

A fiber chuck (FPH-J, Newport) was assembled with two pillow-mounted bearings and a bore diameter ($\phi=3.175$ mm) pulley to hold the rotating portion of fiber. The fiber chuck could accommodate bare fibers up to 250 μm in diameter. An electric motor (RE50, Maxon Motor) fitted with a bore diameter pulley ($\phi=8$ mm) was coupled to the fiber chuck via a pulley belt. The gear ratio and maximum rotation velocity of the loaded electric motor resulted in a maximum UFORJ rotational velocity of 8800 rpm. A short fiber patch cable connectorized on one side was placed in the fiber chuck and secured via a customized fitting. The connectorized end allows for easy substitution of fiber components on the rotating portion of the optical system, in our case a fiber endoscope. The bare, cleaved, end of the patch cable was held by the fiber chuck and inserted into one side of a glass ferrule (FER-1.8–126-GL, OZ Optics) whose diameter (126 μm) was chosen to closely match the diameter of the bare fiber after removal of the buffer. The ferrule had conical shaped ends on

both sides that tapered down to the inner ferrule diameter. This enabled easy damage free insertion of bare fiber on either end.

The glass ferrule did not rotate and was attached to a custom fitting held in an x,y,z adjustment mount. The x,y,z mount allowed for careful alignment of the glass ferrule to the fiber chuck. The nonrotating fiber was passed through the opposite end of the glass ferrule and butted up against the fiber held in the fiber chuck. Both fibers were cleaved before inserting into the glass ferrule. The nonrotating fiber was bonded to the ferrule with epoxy. The glass ferrule was filled with lubricating fluid which served several purposes. It reduced reflections from the cleaved fibers and provided lubrication for the rotating fiber. It also enabled greater separation of the two fibers while maintaining good coupling efficiency.

First we set out to determine the suitability of potential index matching fluids to cover the requisite bandwidth, 355–1360 nm. In addition to being transparent over this range the index matching fluid was ideally chosen to minimize insertion loss due to reflections from, and separation between the two fiber end faces. Losses due to both sources as a function of refractive index (n) and fiber separation (Z_0) have been derived previously [11, 12] and are given by

$$L_{\text{ref}} = -10 \log \left[1 - \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2 \right] \quad (1)$$

$$L_{\text{SMF}} = 8.686 \ln \left[1 + \frac{1}{2} \left(\frac{\lambda Z_0}{\pi n_2 w_0^2} \right)^2 \right] \quad (2)$$

$$L_{\text{MMF}} = -10 \log \left(1 - \frac{Z_0 \text{NA}}{2n_2 r_1} \right) \quad (3)$$

where L is the insertion loss on a dB scale due to reflection (ref), end-face separation in single-mode fiber (SMF), and in multi-mode fiber (MMF). Z_0 is the axial separation between two fiber end-faces, NA is the numerical aperture of the fiber, n_1 is the refractive index of the fiber core, r is the radius of the Gaussian beam diameter in a multi-mode fiber, w_0 is the mode field radius, and n_2 is the refractive index of the medium inside the gap between the fibers. Plots of these three equations are provided in Fig 2 with the following assumptions: We assume an NA of 0.2 for a double clad fiber. r is taken to be the radius of the multimode core, 52.5 μm . w_0 is the mode field radius of the SMF core, 4.6 μm . n_1 is 1.46 and n_2 ranges from 1 to 2.

As expected, losses due to reflection (Fig 2a) are minimized when the refractive index of the lubricant (n_2) matches the index of the fiber core, i.e. $n_1 = n_2$. However, even in the worst

case where the gap is air-filled ($n_2 = 1$) the losses are relatively small at 0.15 dB. Insertion loss due to fiber end-face separation (Figs 2 b and c) is less than 1 dB for separations in excess of 30 μm for all reasonable values of n_2 . In the case of dual clad fiber, one could also estimate the leakage from the single to the multimode core by assuming that all losses go to the multimode core. Under this assumption, eq 2 and Fig 2a can be interpreted as the leakage. Higher n_2 values can provide higher tolerances for fiber end-face separation, making alignment easier and reducing the potential for damage caused by bringing the two fibers into direct contact. Avoiding fiber damage by maintaining space between the two fiber end-faces is expected to be key to achieving long operational lifetimes for the UFORJ. Based on these results, lubricants with refractive index equal to or larger than the fiber core would be the most desirable.

We identified two potential lubricants both with a refractive index of 1.52. The first was an index matching fluid (Norland 105) with low viscosity but unknown absorption spectrum and UV performance. The second was microscope objective immersion oil (Olympus, Type-F) with relatively high viscosity and a manufacturer reported good performance in the UV. Using a 365 nm light source (Mos-Cure mini 365, U-VIX) we made a qualitative measure of the fluorescence from the two candidates. The immersion oil had relatively low fluorescence emission as reported by the manufacturer, however emission from the index matching fluid was much stronger. Based on these results we moved forward with only the immersion oil since the strong fluorescence from the index matching fluid would introduce a strong background for fluorescence imaging.

Next we tested the immersion oil in the UFORJ, filling the capillary with the oil before inserting the freely rotating fiber. For initial testing we chose to assemble the UFORJ with a multimode fiber designed to be used with high power lasers (FG050UGA, Thorlabs). The fiber had a core radius of 50 and a NA of 0.22. The laser source was a 355 nm, nanosecond pulsed laser with a 10 kHz repetition rate. After initially achieving high power throughput the power decreased dramatically within a few minutes. After disassembling the UFORJ we noted physical damage to the fiber end-faces. In order to investigate further, we took bare fibers with freshly cleaved ends and coupled the laser source into the fiber. The laser pulse energy at the exit of the fiber was approximately 3 μJ at 10 kHz repetition rate. The other end of the fiber was submerged in the immersion oil and illuminated for up to 20 minutes. The fiber end-face was then imaged using a fusion splicing system (Vytran, FFS-2000) that offered 0.47 $\mu\text{m}/\text{pixel}$ sampling. Figure 3a shows the results for the MMF in the immersion oil after only a few minutes of exposure. The smooth, cleaved fiber end-face is essentially completely removed with deep pitting across the entire surface of the fiber core. We postulate that while the fluorescence of the immersion oil is low, the absorption is sufficient to cause localized heating and thermal damage to the fiber. Since we were ultimately interested in using double clad fiber in our application we decided to perform similar testing with the SM-9/105/125–20A fiber. It has a multimode core approximately twice bigger than the MMF, which should help mitigate the heating issue by lowering the laser intensity by a factor of ~ 4 . Fig. 3b shows the results after a few minutes exposure. There are some anomalies in the image, but clearly any damage is far less than with the MMF. We then extended the experiment using a fresh fiber to a 20 minute exposure. The results, Fig 3c, show obvious damage with pronounced pitting in the fiber end-face. Clearly

the immersion oil cannot be used as a lubricant for chronic experiments when a UV pulsed laser is used, e.g. fluorescence lifetime imaging. However, the immersion oil may be a good solution for applications that use cw laser sources since the peak intensity would be drastically reduced and likely enable damage free operation.

Since our application, multimodal intravascular imaging with Fluorescence Lifetime Imaging requires a short pulsed UV laser source, we continued our pursuit of a suitable lubricant. The solution we arrived at was to simply lubricate the UFORJ with distilled water. It has the requisite lack of absorption and emission over our desired spectral range. Likewise, with a refractive index of 1.33 it performs (see Fig. 2) fairly well in terms of minimizing insertion loss due to reflection and increasing the tolerance for axial alignment of the two fibers. However, it is normally not considered a good lubricant because of its low viscosity and its tendency to promote oxidation. Neither of those concerns are particularly relevant for this application. The rotating surfaces in contact with water are all smooth glass surfaces and nominally not load bearing, hence the relative increase in friction due to the poor lubricant will not significantly impact the operational lifetime of the UFORJ. As an initial test of the water lubricant performance, we completed similar experiments as described above using bare fibers and inspecting the fiber end-face for damage. The results are in Fig. 3d and 3e. After 20 minutes of exposure there was no observable damage to the fiber.

After assembling the UFORJ using the double clad fiber and distilled water as the lubricant we set about testing the functional performance of the rotary joint. For testing we used two light sources, a 488 nm cw diode laser (Toptica, iBEAM-SMART-PT-488HP) and a swept-laser source centered at 1310 nm with a sweep range of ± 50 nm (Thorlabs, VCSEL, SL1310V1-10048). The former we typically use for frequency domain FLIM applications and the latter for Optical Coherence Tomography. Figure 4(a) shows the results for both wavelengths where the 1310 nm (single mode core) and 488 nm (multimode core) light was coupled into the double clad fiber and the UFORJ rotated through 360° while measuring the output with a power meter. The peak-to-valley variation of the throughput power was 0.07 dB at 488 nm and 0.15 dB at 1310 nm. The mean and standard deviation of the output power are essentially identical for both the rotating and non-rotation case, i.e. within the accuracy of our measurements there is no variation in the insertion loss upon rotation. We also tested the UFORJ during high-speed rotation using fast photodetectors. Figures 4(b) and (c), show the results of measurements with continuous rotation at 8800 rpm (146 Hz) over 20 seconds. The averaged output power was 24 mW from 488 nm and 9.95 mW from 1310 nm with continuous rotation. The variation in the signal from the 488 nm laser on the photodetector, $SD=7.6 \times 10^{-3}$, was similar to the noise when the laser was off, $SD=6.4 \times 10^{-3}$. The intensity noise induced by rotation in the multimode core is therefore less than 1%. The variation in the signal from the 1310 nm laser on the photodetector, $SD=8.3 \times 10^{-4}$, was similar to the noise with the laser off, $SD=7.7 \times 10^{-4}$. The intensity noise induced by rotation in the single mode core is less than 0.1%. For both the single mode and multimode cores, we are near our limits of detection, hence the values quoted should be taken as upper limits.

Finally we examined the integrity of the spatial mode to ensure that light propagating down the single mode core was not bleeding into the multimode core at the interface of the two

fibers. Some imaging technologies, such as Optical Coherence Tomography, suffer from artifacts when executed with multimode fiber. Using commercial beam profilers (Thorlabs, BP104-VIS or IR), we measured the profile of the fiber output after the UFORJ from light launched in both the single mode and multimode cores. The measurements were made while rotating the UFORJ at 8800 rpm. The single mode and multimode core were illuminated with the 1310 nm and 488 nm light, respectively. The beam profiler, either Vis or IR, was placed at a fixed distance from the output of the fiber with no optics between. Only the relative size and shape of the two profiles have meaning. We expected that any significant coupling between the single-mode and multimode core would appear as broadening at the base of an otherwise Gaussian looking profile from the single mode core. Figure 5 shows the results. We first we note that there is no apparent change in the spatial mode comparing the fixed and rotating measurements from the single mode. It is also apparent that there is no significant shoulder on the profiles from the single mode core that could be attributed to 1310 nm light propagating in the multimode core. While there must be some leakage into the multimode core, this evidence suggests that it is small and beyond our current measurement technique..

We have begun using these UFORJ initially for intravascular FLIM imaging. Our experience so far is that the operational lifetime of the UFORJ is at least sufficient for research purposes. The longest imaging session to date was 3 hours with 22 pullback images at rotational velocities of 2400–6000 rpm. At the end of the session the UFORJ was still performing well. Given that the fiber end-faces need not be in direct contact, we expect that operational lifetimes can ultimately be made to rival those of standard commercial FORJ.

We have shown that a lensless fiber optic rotary joint, constructed by butting the ends of a fixed and rotating bare fiber, can be made to operate over a broad spectral range with low insertion loss. Using distilled water as the lubricant and index matching fluid enabled operation down into the UV, at least to 355 nm, and only limited by the absorption spectrum of water and chromatic losses in the chosen fiber. The rotary joint could also be operated at high rotational velocities. It was tested up to 8800 rpm. At this velocity there is very little added intensity noise due to rotational misalignment and no discernable change in the observed spatial mode of the 1310 nm light.

Acknowledgements

We would like to thank Anna Wisniowiecki for her help with the initial UFORJ design and our funding source, National Institutes of Health/National Heart Lung and Blood Institute (NIH/NHLBI) (1R01HL111361).

References

1. Dorsey GF, Components, Hybrids, and Manufacturing Technology, IEEE Transactions on 5, 37–41 (1982).
2. Speer JA, and Koch WW, OE/Fibers, 122–129 (1987).
3. S. Group, “Spotlight (rotating solutions 2008–2015).”
4. Xi J, Zhang A, Liu Z, Liang W, Lin LY, Yu S, and Li X, Opt Lett 39, 2016–2019 (2014). [PubMed: 24686663]
5. Yoo H, Kim JW, Shishkov M, Namati E, Morse T, Shubochkin R, McCarthy JR, Ntziachristos V, Bouma BE, and Jaffer FA, Nature medicine 17, 1680–1684 (2011).

6. Park J, Jo JA, Shrestha S, Pande P, W an Q, and Applegate BE, *Biomed Opt Express* 1, 186–200 (2010). [PubMed: 21258457]
7. Shrestha S, Applegate BE, Park J, Xiao X, Pande P, and Jo JA, *Opt Lett* 35, 2558–2560 (2010). [PubMed: 20680057]
8. Jo JA, Park J, Pande P, Shrestha S, Serafino MJ, Rico Jimenez Jde J, Clubb F, Walton B, Buja LM, Phipps JE, Feldman MD, Adame J, and Applegate BE, *Eur Heart J Cardiovasc Imaging* 16, 910–918 (2015). [PubMed: 25722204]
9. Park J, Pande P, Shrestha S, Clubb F, Applegate BE, and Jo JA, *Atherosclerosis* 220, 394–401 (2012). [PubMed: 22138141]
10. Li X, Chudoba C, Ko T, Pitris C, and Fujimoto JG, *Opt Lett* 25, 1520–1522 (2000). [PubMed: 18066265]
11. Gilsdorf RW, and Palais JC, *Appl Opt* 33, 3440–3445 (1994). [PubMed: 20885725]
12. Mynbaev DK, and Scheiner LL, *Fiber-optic communications technology* (Prentice Hall, 2001).

Fig. 1.
Schematic diagram of UFORJ.

Fig. 2. Insertion loss (a) due to reflections, (b) due to the separation of fiber end-faces for single mode fiber (SMF), (c) due to separation of fiber end-faces for multi-mode fiber (MMF). The fiber was assumed to have a refractive index of 1.46 (n_1).

Fig. 3.

Images of fiber end-face damage after fiber illumination with 355 nm nanosecond laser light using immersion oil (Olympus, Type-F) and distilled water as lubricants (a) MMF after a few minutes with immersion oil, (b) DCF after a few minutes with immersion oil, (c) DCF after 20 minutes with immersion oil, (d) MMF after 20 minutes with water lubricant, (e) DCF after 20 minutes with water lubricant.

Fig. 4.

Measured output power variation with rotation of UFORJ (a) step-wise rotation through one cycle, (b) continuous rotation at 8800 rpm (146 Hz), 488 nm light coupled into the multimode core, (c) continuous rotation at 8800 rpm (146 Hz), 1310 nm light coupled into the single mode core.

Fig. 5.
Measured beam profile from multimode (MM) and single mode (SM) cores of the UFORJ while continuous rotating at 8800 rpm and the single mode core while fixed.