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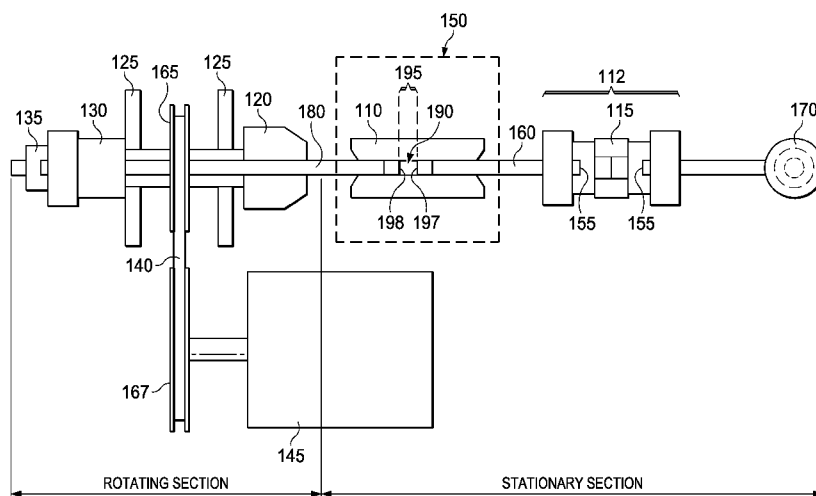


FIG. 1

(57) **Abstract:** A fiber optic rotary joint formed with a capillary tube containing an index-matching fluid and method of forming the same. In one embodiment, the fiber optic rotary joint includes a first stationary optical fiber inserted into and bonded to the capillary tube. The fiber optic rotary joint also includes a second optical fiber, having an end inserted into the capillary tube and in contact with the index-matching fluid, configured to be rotated by a rotatable fiber chuck.

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FIBER OPTIC ROTARY JOINT AND METHOD OF FORMING THE SAME

CROSS REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Application Serial No. 62/305,006 entitled "FIBER OPTIC ROTARY JOINT AND METHOD OF FORMING
5 THE SAME" filed on March 8, 2016, which is incorporated herein by reference.

TECHNICAL FIELD

The present invention relates to fiber optic rotary joints enabling the transmission of optical signals between fibers that rotate relative to one another.

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BACKGROUND

Fiber optic rotary joints ("FORJ") are widely used for transmitting optical signals where one side of a fiber junction rotates freely. Numerous fields take advantage of these devices such as light communication through robotic joints, radar antennas based on slip-ring housings for satellite communication systems, military and civil radars. For applications in
15 medical imaging and sensing, it is sometimes beneficial to use very broad spectral bandwidths, near ultraviolet ("UV") to short-wave infrared ("IR"), as well as more specialized optical fibers such as double clad fiber. These conditions are very challenging for the current set of commercially available fiber optic rotary joints that use lenses in their
20 optical design.

The broad spectral bandwidth necessitates management of chromatic aberration in the lenses important, thereby making it difficult and potentially very expensive to design and construct high performance lens-based fiber optic rotary joints. Likewise, good performance at short wavelengths necessitates a judicious choice of lubricants, since many typical
25 lubricants have strong ultraviolet absorption that can lead to degradation of the lubricant, thermal damage to the optics, and unwanted background fluorescence. Specialized fibers, such as double clad fibers, pose additional challenges such as 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 multi-mode cores.

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The present approaches provide an unacceptable level of insertion loss, fiber abrasion, and fluctuating optical signal power at high spinning speeds. In addition, there is limited ability with present approaches to quantify biomarker contents, and quantitatively and sensitively classify high content as either lipid or collagen. Accordingly, what is needed in the art is a new design approach that addresses and reduces these effects.

SUMMARY

These and other problems are generally solved or circumvented, and technical advantages are generally achieved, by advantageous embodiments of the present invention, including a fiber optic rotary joint formed with a capillary tube containing an index-matching fluid, and method of forming the same. In one embodiment, the fiber optic rotary joint includes a first stationary optical fiber inserted into and bonded to the capillary tube. The fiber optic rotary joint also includes a second optical fiber, having an end inserted into the capillary tube and in contact with the index-matching fluid, configured to be rotated by a rotatable fiber chuck.

The foregoing has outlined rather broadly the features and technical advantages of the present invention in order that the detailed description of the invention that follows may be better understood. Additional features and advantages of the invention will be described hereinafter which form the subject of the claims of the invention. It should be appreciated by those skilled in the art that the conception and specific embodiment disclosed may be readily utilized as a basis for modifying or designing other structures or processes for carrying out the same purposes of the present invention. It should also be realized by those skilled in the art that such equivalent constructions do not depart from the spirit and scope of the invention as set forth in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

FIGUREs 1 and 2 illustrate a partial block diagram and a pictorial view of an embodiment of at least a portion of a fiber optic rotary joint;

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FIGURES 3, 4, and 5 illustrate graphical images showing exemplary insertion loss between transmitting and receiving fibers due to reflections, axial separation of single-mode fibers (“SMFs”) and multi-mode fibers (“MMFs”);

FIGURES 6 through 10 illustrate pictorial views of exemplary results from testing a suitability of an index-matching fluid;

FIGURES 11 through 13 illustrate graphical images of exemplary throughput power variations and power stability during continuous rotation of an optical fiber; and

FIGURE 14 illustrates a flow diagram of an embodiment of a method of forming a fiber optic rotary joint.

Corresponding numerals and symbols in the different figures generally refer to corresponding parts unless otherwise indicated. The figures are drawn to clearly illustrate the relevant aspects of the preferred embodiments and are not necessarily drawn to scale.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

The making and using of the presently preferred embodiments are discussed in detail below. It should be appreciated, however, that the embodiments provide many applicable inventive concepts that can be embodied in a wide variety of specific contexts. The specific embodiments discussed are merely illustrative of specific ways to make and use the invention, and do not limit the scope of the invention.

Embodiments will be described in a specific context, namely, a fiber optic rotary joint (“FORJ”) constructed with optical fibers and methods of forming the same. While the principles of the present invention will be described in the environment of transmitting optical signals through fiber employing a fiber optic rotary joint, any application or related technology that may benefit from a device that can transmit electromagnetic energy through a rotary waveguide joint is well within the broad scope of the present invention.

The fiber optic rotary joint may be applied in 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 should be flushed with a transparent fluid during imaging to clear the blood. This introduces an additional challenge peculiar

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to this application, namely, short bursts of rapid rotation of the FORJ at velocities exceeding 6000 revolutions per minute (“rpm”) for time duration of 4 - 6 seconds. The high rotational velocity is necessary 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. A multimodal system is introduced that integrates OCT with fluorescence lifetime imaging microscopy (“FLIM”) to characterize atherosclerotic plaques and garner information that has previously only been available in postmortem histopathology. Extending this multimodal approach to intravascular imaging invokes the attributes of the FORJ such as extremely broad bandwidth, high rotational velocity, and maintenance of modal integrity with a double clad fiber.

Thus, the combination of optical coherence tomography (“OCT”) and fluorescence lifetime imaging microscopy (“FLIM”) as used in numerous medical and scientific applications leads to the need of a lensless fiber optic rotary joint that can operate over, for instance, a 355-1310 nanometer (“nm”) optical bandwidth and accommodate single-mode, multi-mode, and multi-clad fibers (*e.g.*, double clad fibers) that rotate with respect to one another. The fiber optic rotary joint is introduced herein 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 fiber optic rotary joint introduced herein is capable of both functionalities. As long as the fiber optic rotary joint is achromatic over a wide bandwidth, than it may include a lens, for instance, when changing a numerical aperture (“NA”) of the fiber by adding a small segment of gradient index fiber to an end thereof. As an example, the terms single-mode and multi-mode as used herein refer to the spatial modes of light propagating down the fiber while the terms double, triple, *etc.*, clad refer to the number of cores (or cladding) in the fiber. For instance, a double clad fiber as used herein may have a single-mode (inner) core and a multi-mode (outer) core.

A fiber optic rotary joint can facilitate an intravascular OCT/FLIM system. The intravascular OCT/FLIM system is expected to play an increasing role in clinical imaging of heart patients during cardiac catheterization. Likewise, the OCT/FLIM system may

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find a role in the assessment of the efficacy of therapies. To the extent that these needs come to fruition, the use of a fiber optic rotary joint is advantageous.

Because of their various effective capabilities such as wide broadband signal transmittance, small space for building, and low signal loss, fiber optic rotary joints have been widely used for transmitting optical signals in many fields, for example, for robotic joints controlled with light signals in industry, and radar antennas based on slip-ring housings in military. In clinical fields, especially, by rapidly adapting intravascular imaging via a catheter, fiber optic rotary joints have become the chosen devices in clinical processes. Intravascular imaging of coronary and carotid arteries via a catheter is currently employed to obtain detailed information on the progression of atherosclerosis at high resolution. This information is advantageous for diagnosing and monitoring diseases as well as monitoring and guiding treatment. One of the prevailing catheter-based optical imaging techniques with fiber optic rotary joints is intravascular optical coherence tomography ("IV-OCT"). For evaluating coronary artery diseases such as arterial plaques, IV-OCT comparatively provides more morphological details such as thin-cap fibroatheroma ("TCFA"), smaller minimal lumen area ("MLA") and higher percentage stenosis with high resolution and high speed than intravascular ultrasound ("IVUS").

Although IV-OCT is able to non-invasively produce morphological information with high resolution, there is still a challenge to identify lipid rich plaque, which is based on measuring interferometry and a back-scattered signal. It is becoming increasingly clear that multimodal techniques are beneficial to probe both the morphology and biochemistry of plaques. In order to determine the level of coronary plaque interacted with structural, molecular and cellular processes, it is advantageous to employ a hybrid process with an additional imaging tool that can quantify a biomarker related to plaque growth. An integrated OCT with endogenous FLIM instrument is capable of quantifying biomarkers, which could quantitatively and sensitively classify plaque content as either lipid or collagen. Particular medical applications of a fiber optic rotary joint include, without limitation, endoscopy, light therapy, x-ray imaging, and lab, clinical, and surgical diagnostics.

In order to adapt the OCT/FLIM system for non-destructive intravascular imaging, a catheter-based scanning system should be able to cover a broad wavelength spectrum from ultraviolet ("UV") to infrared ("IR"), which leads to the need for fiber

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optic rotary joints that can operate over, without limitation, a 355-1310 nm bandwidth and accommodate double clad optical fibers. In general, an optical lens for a fiber coupling system is difficult to operate over a 355-1310 nm bandwidth. Also, for the lateral resolution of a catheter based on an optical fiber, a mode-structure should be well
5 maintained while scanning.

Embodiments of a design for a connectorized end on the rotating portion of a rotary joint that allow for changing the catheter endoscope employ deionized water or other fluid for lubrication and index matching for the optical path between the ends of the two fibers. Attempts to form a lensless rotary joint using two fibers with ends butted
10 together have used oil lubricants to index match and provide lubrication. The oils tend to break down when illuminated with ultraviolet light and damage the optical fibers. Prior lensless rotary joints used bare fiber connections that are difficult to work with because of their vulnerability to damage and the difficulty of inserting them into a rotary joint.

In order to qualify the performance of a lensless rotary joint, the coupling
15 efficiency, stability of the coupling efficiency, and mode-structure maintenance may be tested with different speeds of rotation. A fast photodetector can track an output power and its fluctuations. This measurement verifies system signal-to-noise ratio ("SNR"). In order to monitor the mode-structure, a beam profiler can be used.

A prototype system was assembled and tested for optical coupling efficiency and
20 durability. Optical coupling efficiency can be over 90 percent ("%"). The rotary joint can be used and reused over a period of, for instance, at least several days without incident. The tested rotational speed was 8800 revolutions per minute ("rpm"), whereas the maximum rotational speed reported in the literature for a lensless rotary joint is 600 rpm.

As introduced herein, a combination of an OCT and FLIM system is employed in
25 conjunction with a fiber optic rotary joint that can operate over, for instance, a 355-1310 nm bandwidth and accommodate double clad fibers. It should be understood that the fiber optic rotary joint can operate down to, for instance, 200 nm. The resulting ultra-broadband lensless fiber optic rotary joint is able to cover optical wavelengths from
30 ultraviolet to infrared using a double clad fiber. The ultra-broadband lensless fiber optic

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rotary joint can comply with the demands of intravascular scanning device for OCT/FLIM systems.

The fiber optic rotary joint is designed employing a capillary tube that couples a stationary fiber and a rotating fiber (*i.e.*, an optical fiber functional as a first stationary waveguide and a second rotating waveguide). Both fibers may be double clad fibers (*e.g.*, SM-9/105/125-20A, produced by Nufern), enabling the use of single-mode core for OCT and multi-mode core for FLIM. Within the junction, the capillary tube is filled with a fluid such as deionized water for matching a refractive index instead of an immersion oil (*e.g.*, Olympus Immersion Oil Type F), which exhibits fluorescence and can damage a fiber from an ultraviolet laser. The resulting fiber optic rotary joint is able to achieve very low insertion loss (*e.g.*, less than 0.2 decibels (“dB”)) and output angular throughput power fluctuation (*e.g.*, 0.38 dB) with high spinning speed (*e.g.*, 8800 rpm/146 hertz (“Hz”)). With high rotational speed, the fiber optic rotary joint maintains a transverse electromagnetic (“TEM”) mode-structure (*e.g.*, TEM₀₀ mode-structure) from ultraviolet to infrared wavelengths with throughput efficiency above, for instance, 94 percent, which is less than 0.2 dB of insertion loss and less than 0.38 dB of angular power fluctuation during rotation at 8800 rpm/146 Hz. A transverse mode-structure of the output beam during high-speed rotation is well maintained with a TEM₀₀ (Gaussian transverse distribution). As a result, the fiber optic rotary joint technique can be readily applied in the clinical field of optical endoscopic imaging devices as well as other applications.

Turning now to FIGURES 1 and 2, illustrated is a partial block diagram and a pictorial view of an embodiment of at least a portion of a fiber optic rotary joint. The fiber optic rotary joint includes a capillary tube 110 (*e.g.*, a cylindrical glass ferrule/capillary tube such as a FER-1.8-126-GL produced by OZoptics), a first stationary optical fiber 160 and a second optical fiber 180 (a rotatable fiber), a rotatable fiber chuck 120 (*e.g.*, FPH-J produced by Newport), a motor 145 (*e.g.*, RE50 produced by Maxon Motor), and a pulley and belt arrangement (*e.g.*, first and second pulleys 165, 167 and a pulley belt 140).

The shape of both ends of the capillary tube 110 is formed with a conically shaped counter sink to prevent damage of a bare fiber (such as the first stationary optical fiber 160 and the second optical fiber 180) when the bare fiber is passed through the capillary

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tube 110. An inner diameter of the capillary tube 110 is selected to accommodate the diameter of the bare fiber.

The rotatable fiber chuck 120 within the rotating section is coupled to pillow-mounted bearings 125 and the first pulley 165 (a small diameter pulley). In order to use an optical fiber without a buffer jacket, the rotatable fiber chuck 120 is used that accommodates use of an optical fiber with less than, for instance, 250 micrometers ("μm") of outside diameter. The optical fiber at the rotatable fiber chuck 120 is bare double clad fiber that is passed through one side of the capillary tube 110. Depending on an outer diameter of the optical fiber, the rotatable fiber chuck 120 can be changeable. The motor 145 is coupled to a larger diameter second pulley 167 and rotates the rotatable fiber chuck 120 using the pulley belt 140. Based on the diameter ratio of the first and second pulleys 165, 167, a certain rotating speed of the rotatable fiber chuck 120 is achieved.

One part of the second optical fiber 180 that is within the rotatable fiber chuck 120 is able to be connectorized with any commercial fiber connector (such as a ferrule connector or fiber channel/physical contact connector), an angled physical contact connector, and/or a subminiature version A connector. By using a standard fiber connector, the fiber optic rotary joint can be extendable to connect with another optic fiber component. Another side of the second optical fiber 180 at the rotatable fiber chuck 120 is bared and passes through one side of the capillary tube 110, which has, for instance, a 126 micrometer ("μm") diameter of an inner channel to fit a bared fiber. A side of an inner channel has a conical shaped counter sink, which helps for accessibility and to reduce damage at the cleaved surface of a bared fiber. Additionally, an adapter 130 and connectorized fiber end 135 are coupled to an end of the second optical fiber 180 opposite the capillary tube 110 to connect to a system such as an OCT/FLIM system. The adapter 130 combines a rotated fiber with a fiber chuck.

For the stationary section, one end of the first stationary optic fiber 160 is bonded with to the capillary tube 110 and the other end is connected to a light source 170 via, for instance, an optical fiber connector 112 including a mating sleeve 115 and connectorized fiber ends 155. Within an inner channel of the capillary tube 110, the first stationary optic fiber 160 is coupled to the second optical fiber 180. In order to match the refractive

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index within a junction between the first and second optical fibers 160, 180, the inner channel of the capillary tube 110 is filled with a refractive index-matching fluid 190 such as deionized water, which also helps to provide lubrication between the capillary tube 110 and the first and second optical fibers 160, 180. The index-matching fluid 190 is
5 illustrated in a gap 195 between the first and second optical fibers 160, 180. As an example, the refractive index of the index-matching fluid 190 is greater than or equal to 1.3. It is not necessary for the index-matching fluid to match the refractive index of the optical fibers because other properties thereof such as its absorption spectrum play a role in optically coupling the first and second optical fibers 160, 180. A refractive index
10 greater than that of air (such as that of deionized water) can provide a significant role in optically coupling the first and second optical fibers 160, 180. In addition to being transparent over an operating bandwidth, the index-matching fluid should reduce (*e.g.*, minimize) insertion loss due to reflections from, and separation between, the end faces of the first and second optical fibers 160, 180.

15 For an OCT/FLIM application, the index-matching fluid 190 should be appropriate to cover a broadband wavelength from ultraviolet to infrared. Preferably the index-matching fluid 190 should present minimal optical absorption characteristics in the 355-1310 nm bandwidth, and provide less than about 0.5 dB loss. In order to increase coupling efficiency between the first and second optical fibers 160, 180 within the
20 capillary tube 110, the capillary tube 110 is set on a three-dimensional XYZ translation stage 150. In an embodiment, the XYZ translation stage 150 is configured to enable mechanical alignment of one or the other optic fiber along three mutually perpendicular axes. From the XYZ translation stage 150, the first stationary optical fiber 160 is able to adjust lateral misalignment and axial separation to the second rotatable optical fiber 180
25 in order to improve or otherwise optimize coupling efficiency. From the XYZ translation stage 150, the first stationary optical fiber 160 is able to be aligned coaxially and be close to the second rotatable optical fiber 180 at the rotatable fiber chuck 120.

As further illustrated in FIGURE 1, a first small segment 197 and a second small segment 198 of gradient index fiber can be spliced to an end of the first stationary optical
30 fiber 160 and the second optical fiber 180, respectively, to improve optical coupling therebetween. In an embodiment, the end of the first stationary optical fiber 160 and the

second optical fiber 180 (and/or the end of the first and second small segments 197, 198 of gradient index fiber(s)) can be shaped with curvature such as shaped with a spherical curvature to provide further improvement in optical coupling therebetween. As an example, the coupling loss between the fibers is less than 0.1 dB.

5 In order to validate the performance of the fiber optic rotary joint, suitability of an index-matching solution, the coupling efficiency, stability of the coupling efficiency, and mode-structure maintenance, the transmission mode-structure was tested with different rotation speeds of the rotatable optical fiber. The suitability of an index-matching solution, fluorescence emission and maintainability were checked of a bared fiber optic
10 condition between an index-matching fluid and a bared fiber, which is connected with a pulsed 355 nm or 488 nm diode laser or a 1310 nm swept source (SL1310V1-10048, produced by Thorlabs). A fast photo detector was placed on the end of the rotating fiber for monitoring throughput power and power fluctuation during rotation of the fiber. Also, in order to monitor the transmission mode-structure during rotation, a beam profiler
15 (BP104-VIS/IR, produced by Thorlabs) was used.

In order to find and check suitability of an index-matching solution for OCT/FLIM applications, an index matching liquid (refractive index: 1.52, Norland 105), an immersion oil for fluorescence microscope (refractive index: 1.52, Type-F, from Olympus), and deionized (“DI”) water (refractive index: 1.33) were used and tested.
20 Equation (1), (2), and (3) describe insertion loss caused by mechanical misalignment from fiber separation and reflection. The insertion loss in terms of a refractive index of an index-matching solution with a gap between a transmitting and a receiving fiber can be theoretically estimated employing equations [1] to [3]:

$$L_{sep,MMF} = -10 \log \left(1 - \frac{Z_0 NA}{2n_2 r_1} \right) \quad [1]$$

$$25 \quad L_{sep,SMF} = 8.686 \ln \left[1 + \frac{1}{2} \left(\frac{\lambda Z_0}{\pi n_2 w_0^2} \right)^2 \right] \quad [2]$$

$$L_{fresnel} = -10 \log \left[1 - \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2 \right], \quad [3]$$

where L is the insertion loss on a decibel (“dB”) scale due to reflection (ref), end-face separation in single-mode fiber (“SMF”), and in multi-mode fiber (“MMF”). Z_0 is an axial separation between two fiber end-faces, NA is a numerical aperture of a fiber, n_1 is a

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refractive index of a fiber, r_1 is the radius of the Gaussian beam diameter in a multi-mode fiber, w_0 is the spot size or mode field radius of a transmitting fiber, and n_2 is the refractive index of the medium inside the gap between the fibers.

Plots of equations (1), (2), and (3) are provided in FIGURES 3, 4, and 5, illustrating performance of an embodiment with the following assumptions. A numerical aperture (“NA”) of 0.24 is assumed for a double clad fiber. The radius r_1 is taken to be the radius of the multi-mode core, 52.5 μm . The spot size w_0 is the mode field radius of the SMF core, 10.5 μm . The refractive index n_1 is 1.46 and the refractive index n_2 ranges from 1 to 2. In particular, FIGURE 3 illustrates insertion loss due to reflections with a line 310. FIGURE 4 illustrates with the several lines shown for various refractive indices and identified on the graph insertion loss due to separation of fiber end faces for a single-mode fiber (“SMF”). FIGURE 5 illustrates insertion loss with the several lines shown and identified on the graph due to separation of fiber end faces for a multi-mode fiber (“MMF”). The fiber is assumed to have a refractive index of 1.46 (n_1).

As expected, losses due to reflection (as illustrated in FIGURE 3) are reduced when the refractive index (n_2) of the lubricant 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 (as illustrated in FIGURES 4 and 5) is less than 1 dB for separations in excess of 30 μm for reasonable values of index of refraction n_2 . In the case of a double clad fiber, one could also estimate the leakage from the single- to the multi-mode core by assuming that the losses go to the multi-mode core. Under this assumption, equation 2 and FIGURE 4 can be interpreted as the leakage. However, higher index of refraction 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 fiber ends into direct contact. Avoiding fiber damage by maintaining space between the two fiber end faces would be beneficial to achieving longer operational lifetimes for the fiber optic rotary joint. Based on these results, lubricants with refractive index equal to or larger than the fiber core would be desirable.

The following equations provide further estimates for the insertion loss.

$$L_{\text{SMF}} = 8.686 \ln \left[1 + \frac{1}{2} \left(\frac{2r_1 \text{NA} Z_0}{V w_0 n_2} \right)^2 \right] \quad [4]$$

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$$L_{\text{MMF}} = -10 \log \left(1 - \frac{Z_0 \text{NA}}{2n_2 r_1} \right) \quad [5]$$

Equations 4 and 5 describe the insertion losses L due to the separation of the two fibers Z_0 as function of the numerical aperture (“NA”), wherein V represents the fiber’s V-number. If the NA of the light exiting the fiber is reduced, the insertion losses L at greater separation Z_0 are also reduced. In other words, if the NA is reduced, the separation between the two fibers may be larger while maintaining low losses. That will make it easier to align and reduce the risk of damaging the end face of the optical fibers. There are a number of ways to modify the NA. One method is to shape the end face of the fiber, providing some curvature. A relatively small curvature can positively impact the insertion loss L , while having a negligible impact on the achromatic behavior of the fiber optic rotary joint. A second method would be to splice a small segment of gradient index fiber to the end. It would have a similar effect, but have the advantage of having a flat end face and not have dependence on the refractive index of the index-matching fluid. As an example, see FIGURE 1 and the related text above. If it is desirable to use a curved fiber end face of an optical fiber to act as a lens, then the refractive index of the index-matching fluid should not match that of the optical fiber. It is recognized that the greater differences between the refractive indices, the less curvature is necessary to be formed on the end of the fiber to obtain the same change in the numerical aperture.

With continuing reference to FIGURE 1, the length of gap 195 may be short enough to produce an insertion loss of less than 1 dB. As an example, the term Z_0/n_2 can be used as a guide with respect to the insertion loss. In that case, to obtain an insertion loss of less than 1 dB, Z_0/n_2 is less than 25 μm for the single mode fiber (see, *e.g.*, equation 4) and Z_0/n_2 is less than 163 μm for the multi-mode fiber (see, *e.g.*, equation 5). Note that this is still specific to a particular fiber since losses are also dependent on fiber specific parameters (*e.g.*, NA, mode field radius). It does, however, capture the relationship between refractive index of the fluid (n_2) and the separation at a target insertion loss. It should also be understood that insertion losses, in general, are provided as a maximum value (*e.g.*, less than 2 dB) and operational values (*e.g.*, less than 0.5 or 1 dB).

Two potential lubricants were identified, both with a refractive index of 1.52. The first was an index matching fluid (Norland 105) with low viscosity but unknown

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absorption spectrum and ultraviolet performance. The second was microscope objective immersion oil (Olympus, Type-F) with relatively high viscosity and manufacturer reported good performance in the ultraviolet. Using a 365 nm light source (Mos-Cure mini 365, U-VIX), a qualitative measure was made 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, the immersion oil was used in further work since strong fluorescence from an index matching fluid introduces a strong background level for fluorescence imaging.

Next, the immersion oil was tested for in the fiber optic rotary joint, filling the capillary tube with the oil before inserting the freely rotating fiber. For initial testing, the fiber optic rotary joint included a multi-mode fiber designed to be used with high power lasers (*e.g.*, FG050UGA, Thorlabs). The fiber had a core radius of 25 μm and a NA of 0.22. The laser source was a 355 nm, nanosecond pulsed laser with a 10 kilohertz (“kHz”) repetition rate. After initially achieving high power throughput, the power decreased dramatically within a few minutes. After disassembling the fiber optic rotary joint, there was physical damage to the fiber end faces.

Turning now to FIGUREs 6 through 10, illustrated are pictorial views of exemplary results from testing a suitability of an index-matching fluid. FIGURE 6 illustrates an end view and side view of a multi-mode fiber after a few minutes of submerging into an immersion oil (bar size about 50 μm). FIGURE 7 illustrates an end view and side view of a double clad fiber after a few minutes of submerging into the immersion oil. FIGURE 8 illustrates an end view and side view of a double clad fiber after 20 minutes of submerging into the immersion oil. FIGURE 9 illustrates an end view and side view of a multi-mode fiber after 20 minutes of submerging in deionized water. FIGURE 10 illustrates an end view and side view of a double clad fiber after 20 minutes of submerging into the deionized water. In each case, the end view is shown in the image on the left, and the side view is shown in the image on the right.

In order to check auto-fluorescence emission, ultraviolet light was shined directly onto an index-matching fluid. By submerging a bare fiber connected with a pulsed ultraviolet laser into an index-matching fluid for a few minutes, a cleaved surface

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condition of a fiber was checked. Fluorescence emission from an index matching fluid and immersion oil was tested using an ultraviolet lamp (Mos-Cure Mini 365, U-VIX).

A commercial index matching fluid has fluorescence emissions, which is not appropriate for interrupting a sample signal for the FLIM analysis. In order to remove the
5 fluorescence background signal, immersion oil and deionized water were tested, which does have substantially less auto-fluorescence emission in the ultraviolet range. The immersion oil and deionized water did not exhibit auto-fluorescence emission from exposure of the same ultraviolet lamp or a coupled ultraviolet laser.

When immersion oil was used as the index-matching fluid to fill a junction
10 between two bared fiber ends butted together, the throughput power ratio was dramatically decreased within a few minutes. In order to validate the issue of throughput power loss, a cleaved double clad fiber and multi-mode fiber coupled with a pulsed 355 nm laser were submerged and illuminated in immersion oil for 20 minutes. Pulse energy from a fiber end was 3 micro-joules (“ μJ ”) at 10 kilohertz (“kHz”). For checking the
15 condition of a fiber end face, a core imaging system was used (FFS-2000, Vytran) that can offer a high-resolution image with about 0.47 microns/pixel (“ $\mu\text{m}/\text{pixel}$ ”).

As illustrated in the image on the right side of FIGURE 6, a cleaved fiber end face was substantially degraded when illuminated with a pulsed 355 nm laser. The smooth, cleaved fiber end face is essentially completely removed with deep pitting across the
20 entire surface of the fiber core. While the fluorescence of the immersion oil is low, the absorption is sufficient to cause localized heating and thermal damage to the fiber.

Turning now to the double clad fiber, a similar test was performed thereon (*e.g.*, SM-9/105/125-20A fiber). It has a multi-mode core approximately twice as big as the MMF, which should help mitigate the heating issue by lowering the laser intensity by a
25 factor of about four. In the case of a double clad fiber, as illustrated by the spots in the image on the left side of FIGURE 7, after two minutes in the immersion oil, the core of the multi-mode fiber was pitted, and a damaged area of the fiber is visible on the cladding area. In the image shown on the right side of FIGURE 7, drops of oil remaining on the fiber are visible. In the image shown on the left side of FIGURE 8, after 20 minutes,
30 substantial area of the fiber was substantially pitted and damaged. In FIGURES 9 and 10, deionized water did not result in damage to the cleaved surface of either a multi-mode

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fiber or a double clad fiber. Based on a condition of a damaged fiber end face, destruction of cladding and core of a fiber changes a numerical aperture and/or a condition of total internal reflection to transmit a coupled light, which causes a loss in coupling efficiency between the optical fibers.

5 In order to obtain a stable sample signal, which is based on the light source intensity from the fiber optical joint scanning system, throughput power efficiency and fluctuation should be very stable during scanning. Output beam power and fluctuation from the fiber optical rotary joint were monitored at high rotating speed (about 8800 rpm, 146 Hz). Coupled light source wavelengths from a 488 nm diode laser for the FLIM
10 application and 1310 nm for OCT application were used. By using a high speed photo-detector, throughput power and fluctuation were measured in real time. Averaged input power from 488 and 1310 nm light sources is 25 milliwatts ("mW") and 10 mW.

 After assembling a fiber optic rotary joint using double clad fiber and deionized water as the lubricant, the functional performance of the rotary joint was tested. For
15 testing, two lights sources were used, a 488 nm continuous wave ("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 is typically used for frequency domain FLIM applications and the latter for Optical Coherence Tomography.

20 Turning now FIGURES 11 through 13, illustrated are graphical images of exemplary throughput power variations and power stability during continuous rotation of an optical fiber. In FIGURE 11, illustrated is measured normalized angular output power variation (overlying lines 1120) from coupled optical signals either at 488 and 1310 nm with rotation of a fiber optic rotary joint with step-wise rotation through one cycle. Also
25 shown in FIGURE 11 is normalized power 1110 with lasers turned off. The lines 1120 substantially lie on top of each other. In FIGURE 12, illustrated is throughput power stability 1210 (both fixed or rotated, the lines lying essentially on top of each other) from a 488 nm laser coupled to a multi-mode fiber core with a continuous rotation rate of 8800 rpm (146 Hz) over 20 seconds. There is no substantial fluctuation in measured output
30 power after approximately 10 seconds into the experiment when the respective laser was disabled. At the time 1220, the laser is turned off. In FIGURE 13, illustrated is

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throughput power stability (lines 1320 lying essentially on top of each other) from a 1310 nm laser coupled to a single-mode core (both fixed or rotated) with a continuous rotational rate of 8800 rpm (146 Hz) over 20 seconds. At the time 1330, the laser is turned off. Again, there is essentially no fluctuation in measured output power after
5 approximately 10 seconds into the experiment when the respective laser was disabled. The small value of power variation is within an acceptable range of variation.

Thus, FIGURE 11 shows the results for both wavelengths where the 1310 nm (single-mode core) and 488 nm (multi-mode core) light was coupled into the double clad fiber and the fiber optic rotary joint rotated through 360 degrees while measuring the
10 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 the measurements there is no variation in the insertion loss upon rotation. The fiber optic rotary joint was also tested during high-speed rotation using fast
15 photodetectors.

FIGURES 12 and 13 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, standard deviation $SD=7.6 \times 10^{-3}$, was similar
20 to the noise when the laser was off, $SD=6.4 \times 10^{-3}$. The intensity of the noise induced by rotation in the multi-mode core is therefore less than 1 percent. 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 percent. For both the single-mode and multi-mode cores, limits
25 of detection are approached, and hence the values quoted should be taken as upper limits.

In a general point-scanning application of optical imaging, a spot size of one focused beam at a sample determines spatial resolution. By using a laser source that has good beam shape such as TEM_{00} (Gaussian) spatial mode, good spatial resolution can be achieved. In order to generate an interferometry signal, which is the fundamental signal
30 of OCT, the mode-structure of a light source should be TEM_{00} .

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Since multimodal intravascular imaging with fluorescence lifetime imaging employs a short pulsed UV laser source, pursuit of a suitable lubricant continued. A solution is to simply lubricate the fiber optic rotary joint with deionized water. It has the requisite lack of absorption and emission over the desired spectral range. Likewise, with a refractive index of 1.33, it performs well in terms of reducing or minimizing insertion loss due to reflection and increasing 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 is particularly important for this exemplary application. The rotating surfaces in contact with water are all smooth glass surfaces and are nominally not load bearing. Hence the relative increase in friction due to poor lubrication will not significantly impact operational lifetime of the fiber optic rotary joint. As an initial test of the water lubricant performance, similar experiments were completed as described hereinabove using bare fibers and inspecting the fiber end-faces for damage. After twenty minutes of exposure, there was no observable damage to the fiber.

Turning now to FIGURE 14, illustrated is a flow diagram of an embodiment of a method of forming a fiber optic rotary joint. The process flow begins in start step or module 1400. In a step or module 1405, an index-matching fluid is provided in a capillary tube, an end of which may be conically shaped. The index-matching fluid may include deionized water and an alcohol or fluid that is optically transparent at a bandwidth of 355-1310 nm. In an embodiment, a refractive index of the index-matching fluid matches a refractive index of a first stationary optical fiber and a second optical fiber, and the first stationary optical fiber and the second optical fiber may include double clad fibers.

In a step or module 1410, a first stationary optical fiber is inserted into the capillary tube. The first stationary optical fiber is then bonded to the capillary tube in a step or module 1415. In a step or module 1420, an end of the first stationary optical fiber is coupled to a light source via, for instance, an optical fiber connector. The optical fiber connector may include connectorized fiber ends and a mating sleeve. In a step or module 1425, an end of a second optical fiber is inserted into the capillary tube and in contact with the index-matching fluid. The second optical fiber is coupled to and held by a

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rotatable fiber chuck, in a step or module 1430, which is supported by a pillow-mounted bearing(s) via a step or module 1435. In a step or module 1440, the pillow-mounted bearing(s) are coupled to a pulley and belt arrangement, which is coupled to a motor via a step or module 1445. In a step or module 1450, an XYZ translation stage is coupled to the pillow-mounted bearing(s), and the second optical fiber is aligned within the capillary tube with the XYZ translation stage via a step or module 1455. In a step or module 1460, the second optical fiber is rotated with respect to the first stationary optical fiber within the capillary tube by the rotatable fiber chuck via a motor. The method ends at a step or module 1465.

A fiber optic rotary joint has thus been described herein for OCT/FLIM and other applications. By using double clad fiber and an index-matching fluid (providing refractive index matching and lubrication), the fiber optic rotary joint is capable of covering ultra-broadband wavelengths from ultraviolet to infrared (*e.g.*, 355-1310 nm). With a high rotational speed (such as 8800 rpm), the fiber optic rotary joint exhibits low insertion loss (*e.g.*, less than 0.2 dB) and low angular power variations. The resulting fiber optic rotary joint can be readily adopted in clinical applications.

The integrity of the spatial mode can also be examined to ensure that light propagating down a single-mode core does not bleed into a multi-mode core at the interface of the two fibers. Some imaging technologies, such as OCT, suffer from artifacts when executed with a multi-mode fiber. Using commercial beam profilers (Thorlabs, BP104-VIS (visible) or IR (infrared)), the profile of the fiber output can be measured after the fiber optic rotary joint from light launches in both the single-mode and multi-mode cores. The measurements were taken while rotating the fiber optic rotary joint at 8800 rpm. The single-mode and multi-mode cores were illuminated with the 1310 and 488 nm light, respectively. The beam profiler, either VIS (visible) or IR (infrared), 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. It was expected that any significant coupling between the single-mode and multi-mode core would appear as broadening at the base of an otherwise Gaussian looking profile from the single-mode core. It is first noted that there is no apparent change in the spatial mode, comparing the fixed and rotating measurements from the single-mode core. It is also

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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 multi-mode core. While there may be some leakage into the multi-mode core, this evidence suggests that it is small and beyond our current measurement techniques.

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

 Those skilled in the art should understand that the previously described
15 embodiments of a fiber optic rotary joint and related methods of forming and operating the same are submitted for illustrative purposes only. While the fiber optic rotary joint may be applied in clinical applications, the fiber optic rotary joint may also be applied to other systems such as, without limitation, a rotary waveguide coupled by a rotary waveguide joint to a stationary waveguide.

20 Also, although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made herein without departing from the spirit and scope of the invention as defined by the appended claims. For example, many of the processes discussed above can be implemented in different methodologies and replaced by other processes, or a
25 combination thereof.

 Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process, machine, manufacture, composition of matter, means, methods, and steps described in the specification. As one of ordinary skill in the art will readily appreciate from the disclosure of the present invention, processes,
30 machines, manufacture, compositions of matter, means, methods, or steps, presently existing or later to be developed, that perform substantially the same function or achieve

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substantially the same result as the corresponding embodiments described herein may be utilized according to the present invention. Accordingly, the appended claims are intended to include within their scope such processes, machines, manufacture, compositions of matter, means, methods, or steps.

WHAT IS CLAIMED IS:

1. A fiber optic rotary joint, comprising:
a capillary tube (110) containing an index-matching fluid (190);
5 a first stationary optical fiber (160) inserted into and bonded to said capillary tube (110); and
a second optical fiber (180), having an end inserted into said capillary tube (110) and in contact with said index-matching fluid (190), configured to be rotated by a rotatable fiber chuck (120).
- 10 2. The fiber optic rotary joint as recited in Claim 1 further comprising a pillow-mounted bearing (125) configured to support said rotatable fiber chuck (120).
3. The fiber optic rotary joint as recited in Claim 2 further comprising an XYZ translation stage (150) coupled to said pillow-mounted bearing (125) and configured to align said second optical fiber (180) within said capillary tube (110).
- 15 4. The fiber optic rotary joint as recited in Claim 1 further comprising a motor (145) configured to rotate said rotatable fiber chuck (120).
5. The fiber optic rotary joint as recited in Claim 1 further comprising an optical fiber connector (112) coupled to an end of said first stationary optical fiber (160).
6. The fiber optic rotary joint as recited in Claim 1 further comprising a light
20 source (170) coupled to an end of said first stationary optical fiber (160).
7. The fiber optic rotary joint as recited in Claim 1 wherein said index-matching fluid (190) comprises at least one of deionized water and an alcohol that is optically transparent at a bandwidth of 355-1310 nanometers.
8. The fiber optic rotary joint as recited in Claim 1 wherein a refractive index
25 of said index-matching fluid (190) matches a refractive index of said first stationary optical fiber (160) and said second optical fiber (180).
9. The fiber optic rotary joint as recited in Claim 1 wherein an end of said capillary tube (110) is conically shaped.

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10. The fiber optic rotary joint as recited in Claim 1 wherein said first stationary optical fiber (160) and said second optical fiber (180) comprise double clad fibers.

11. A method of forming a fiber optic rotary joint, comprising:
5 providing (1405) an index-matching fluid (190) in a capillary tube (110);
inserting (1410) a first stationary optical fiber (160) into said capillary tube (110);
bonding (1415) said first stationary optical fiber (160) to said capillary tube (110);
and
inserting (1425) an end of a second optical fiber (180) into said capillary tube
10 (110) and in contact with said index-matching fluid (190).

12. The method as recited in Claim 11 further comprising supporting (1435) a rotatable fiber chuck (120) coupled to said second optical fiber (180) with a pillow-mounted bearing (125).

13. The method as recited in Claim 12, further comprising:
15 coupling (1450) an XYZ translation stage (150) to said pillow-mounted bearing (125); and
aligning (1455) said second optical fiber (180) within said capillary tube (110).

14. The method as recited in Claim 11 wherein said second optical fiber (180) is configured to be rotated (1460) by a rotatable fiber chuck (120) coupled to a motor
20 (145).

15. The method as recited in Claim 11 further comprising coupling (1420) an optical fiber connector (112) to an end of said first stationary optical fiber (160).

16. The method as recited in Claim 11 further comprising coupling (1420) a light source (170) to an end of said first stationary optical fiber (160).

17. The method as recited in Claim 11 wherein said index-matching fluid
25 (190) comprises at least one of deionized water and an alcohol that is optically transparent at a bandwidth of 355-1310 nanometers.

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18. The method as recited in Claim 11 wherein a refractive index of said index-matching fluid (190) matches a refractive index of said first stationary optical fiber (160) and said second optical fiber (180).

19. The method as recited in Claim 11 wherein an end of said capillary tube
5 (110) is conically shaped.

20. The method as recited in Claim 11 wherein said first stationary optical fiber (160) and said second optical fiber (180) comprise double clad fibers.

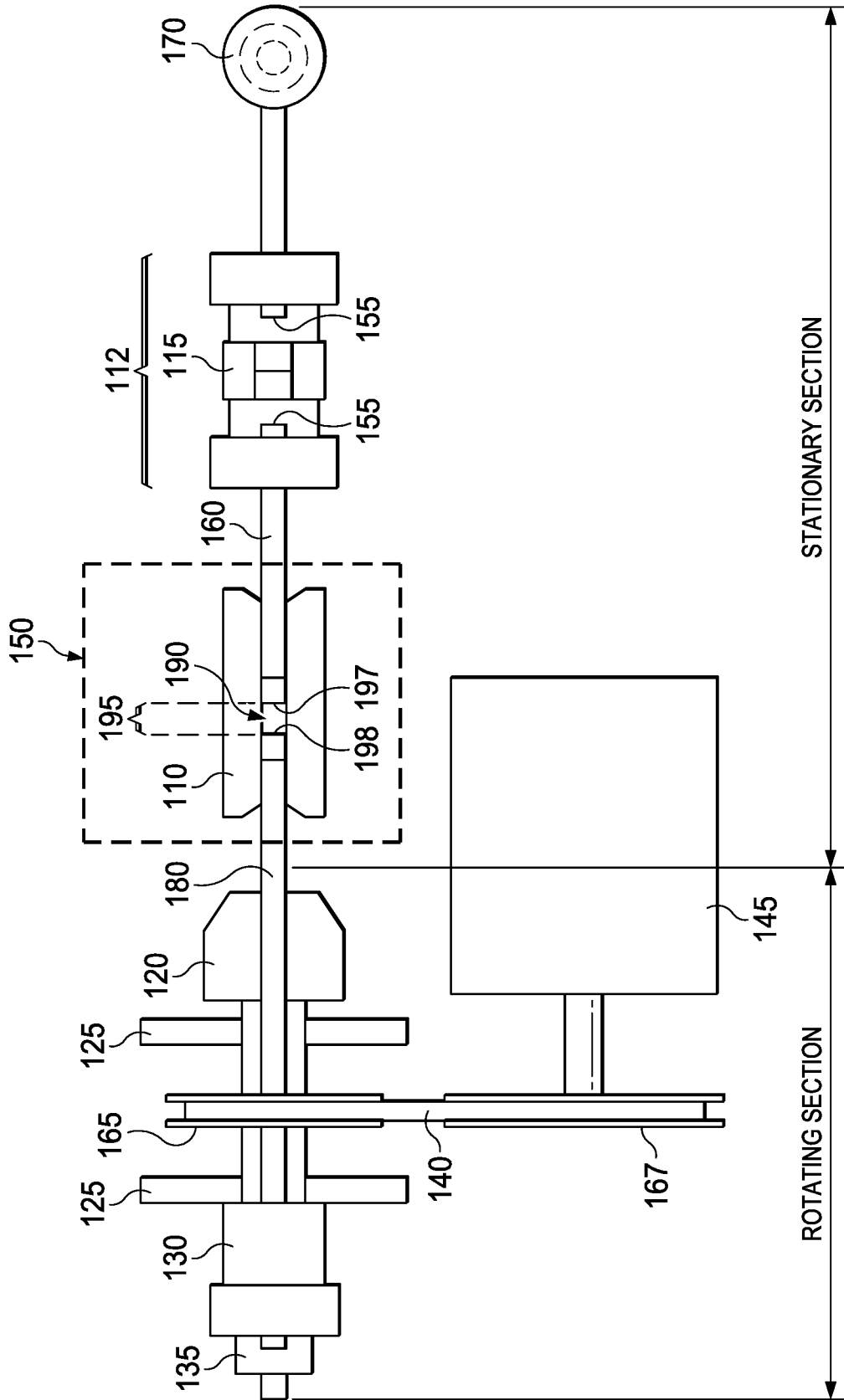


FIG. 1

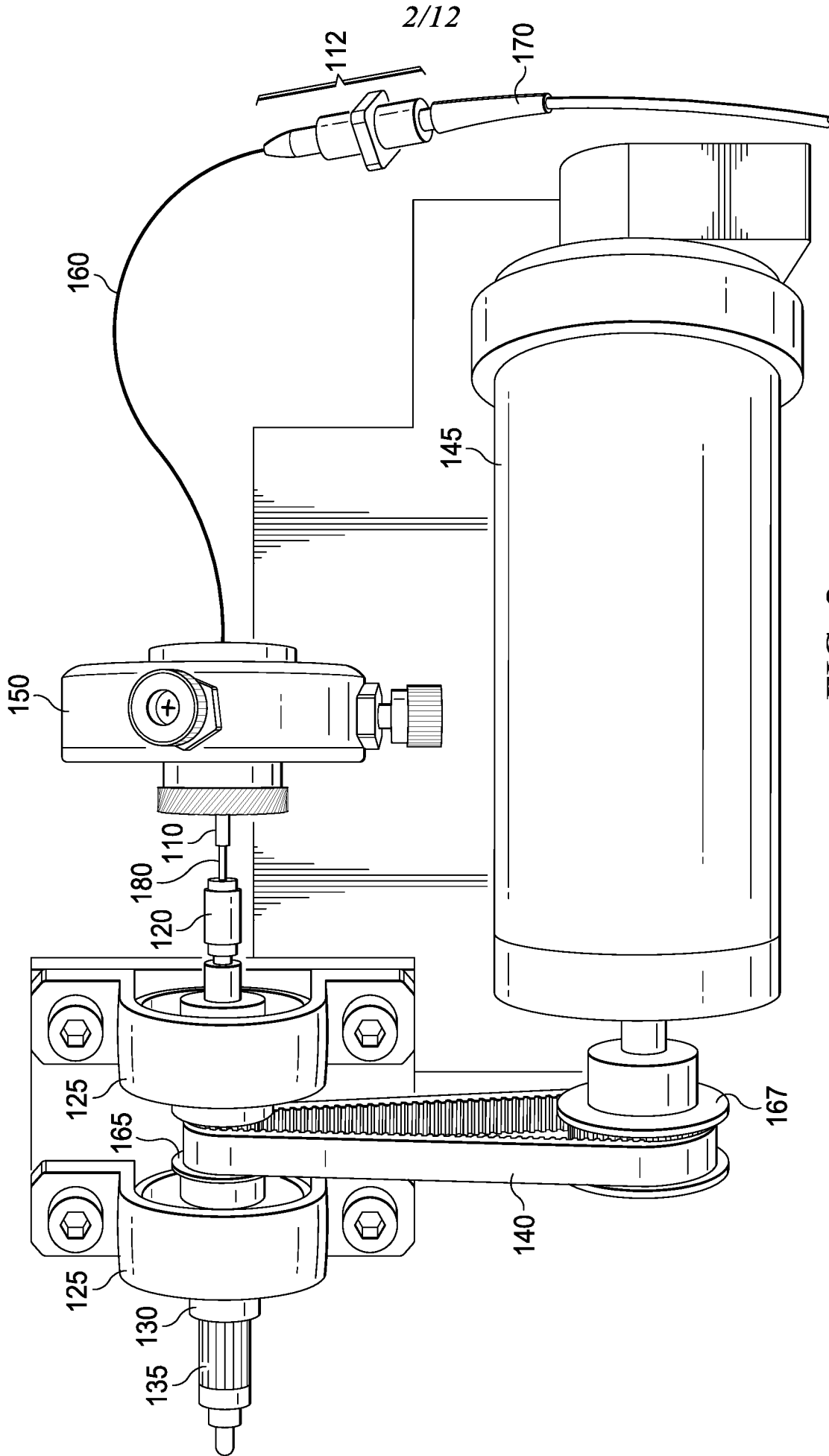


FIG. 2

FIG. 3

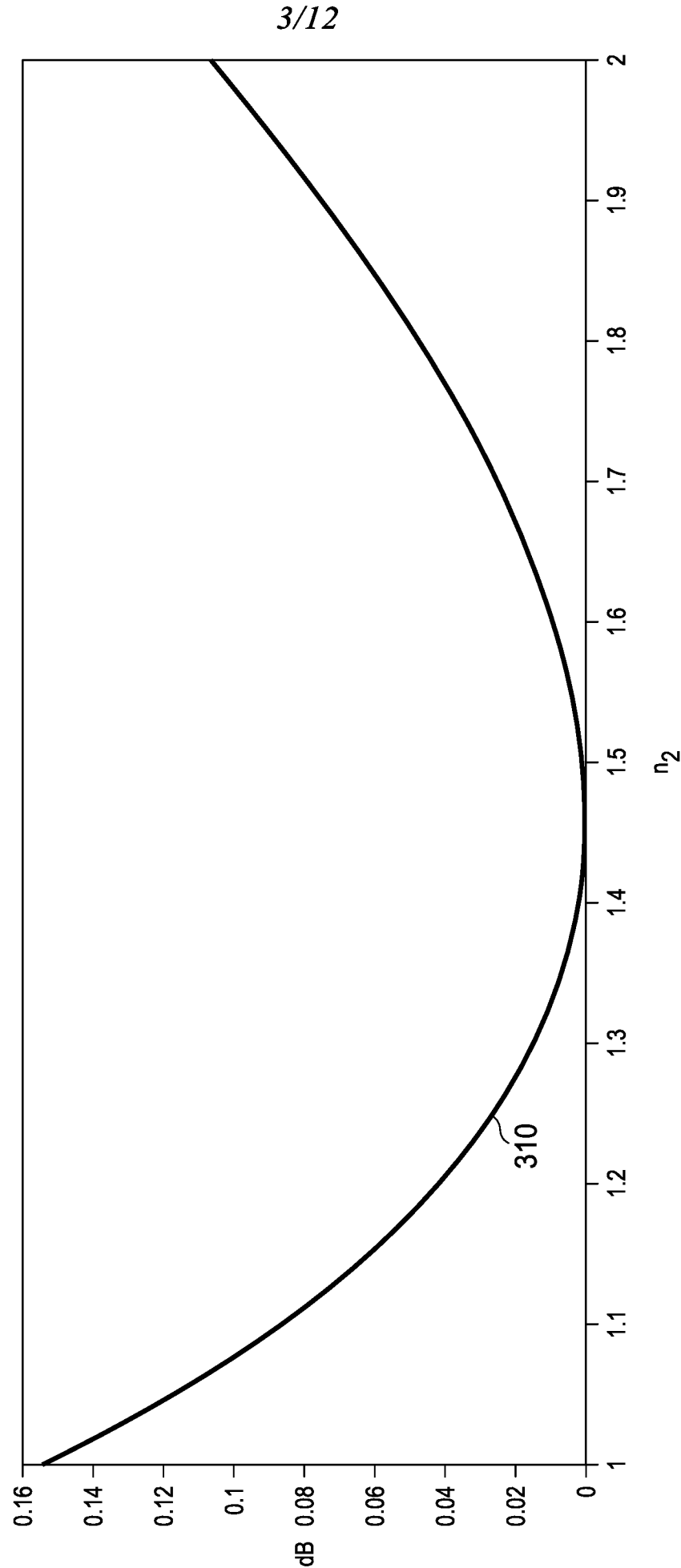


FIG. 4

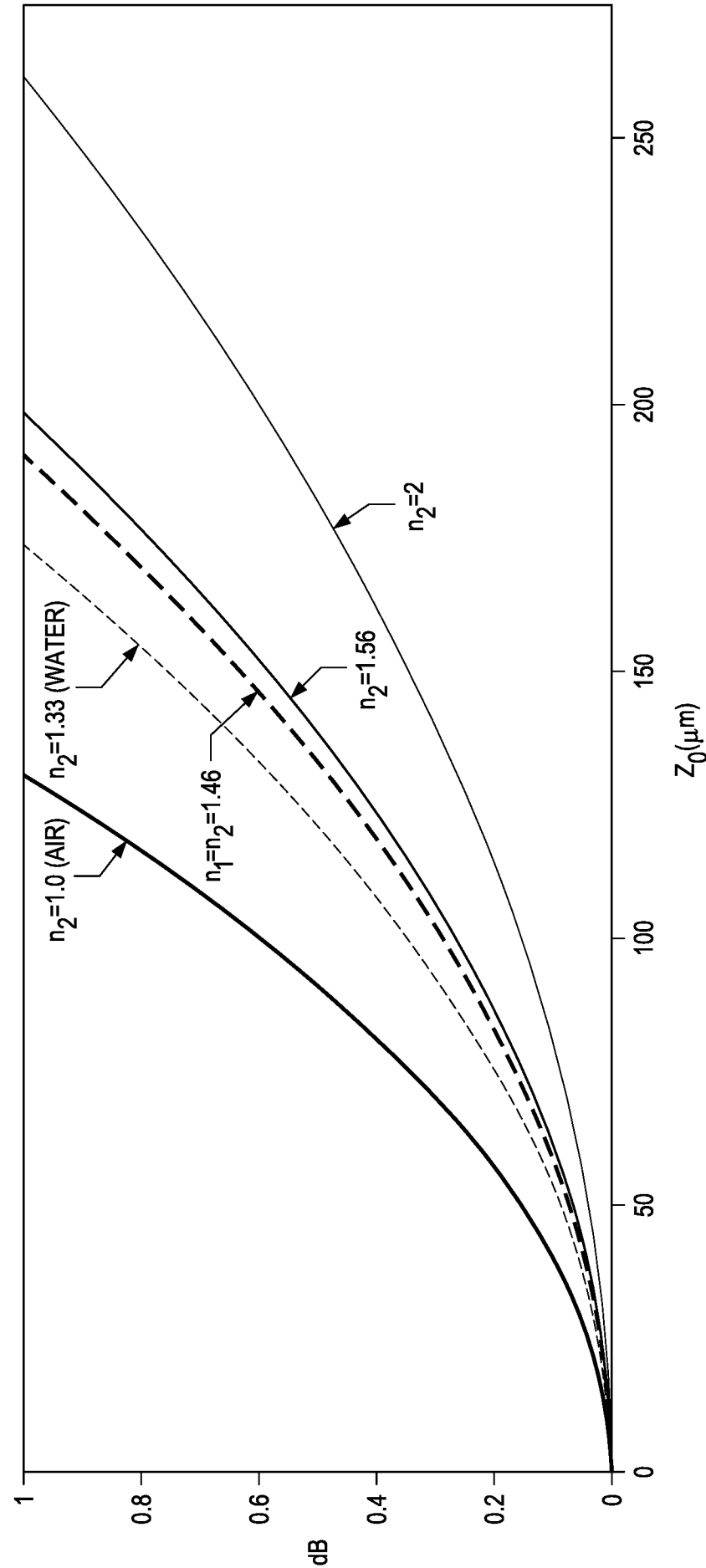
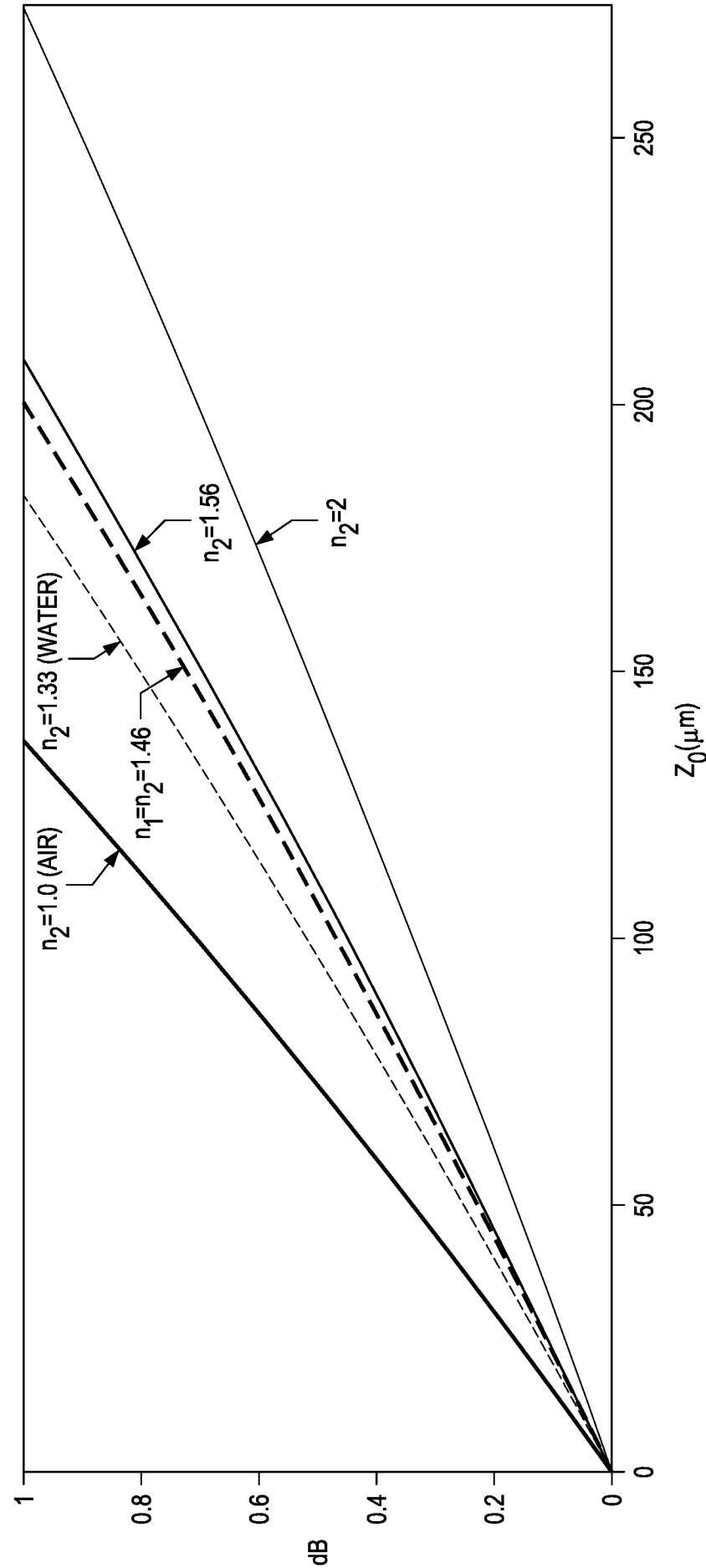


FIG. 5



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AFTER A FEW MINUTES IN OIL (MMF)

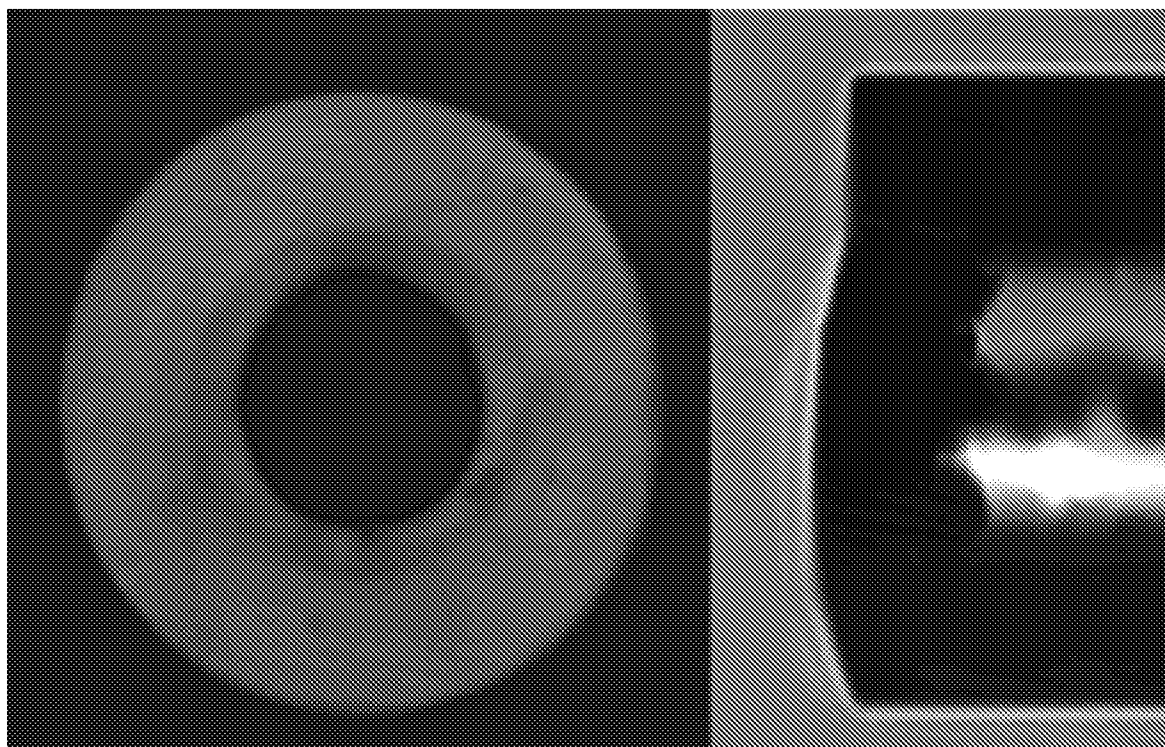


FIG. 6

AFTER A FEW MINUTES IN OIL (DUAL CLAD)

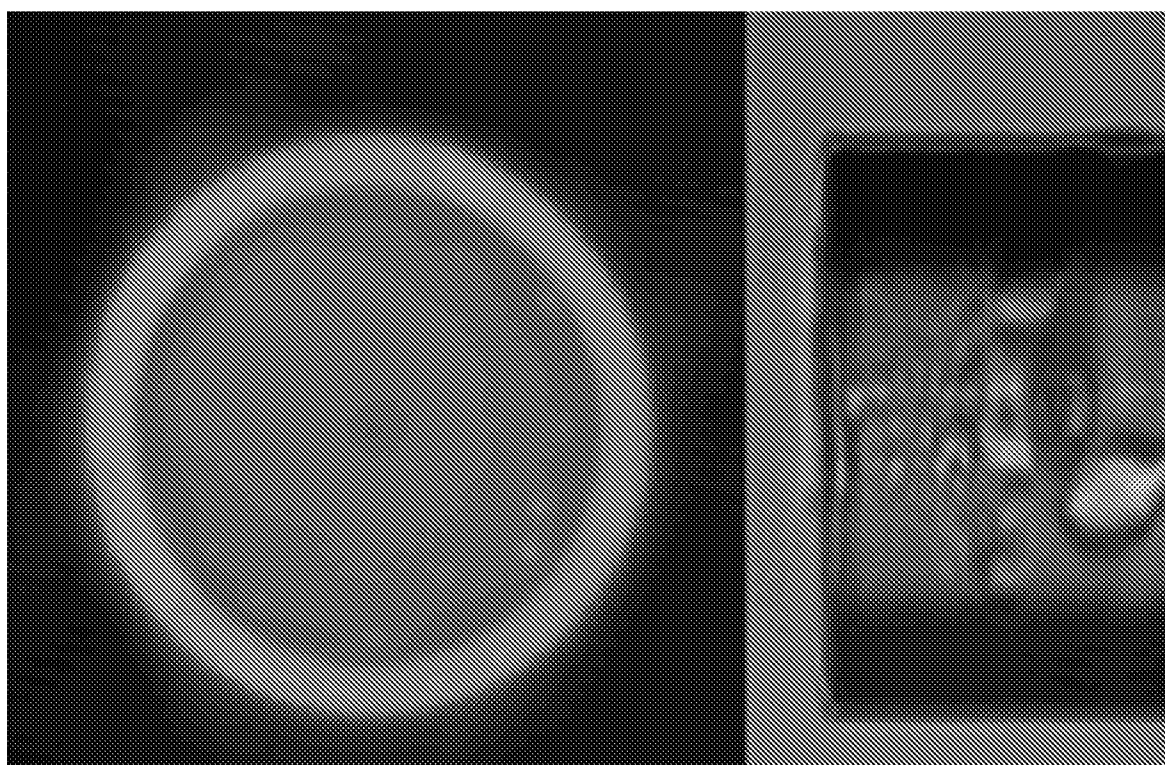


FIG. 7

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AFTER 20 MINUTES IN OIL (DUAL CLAD)

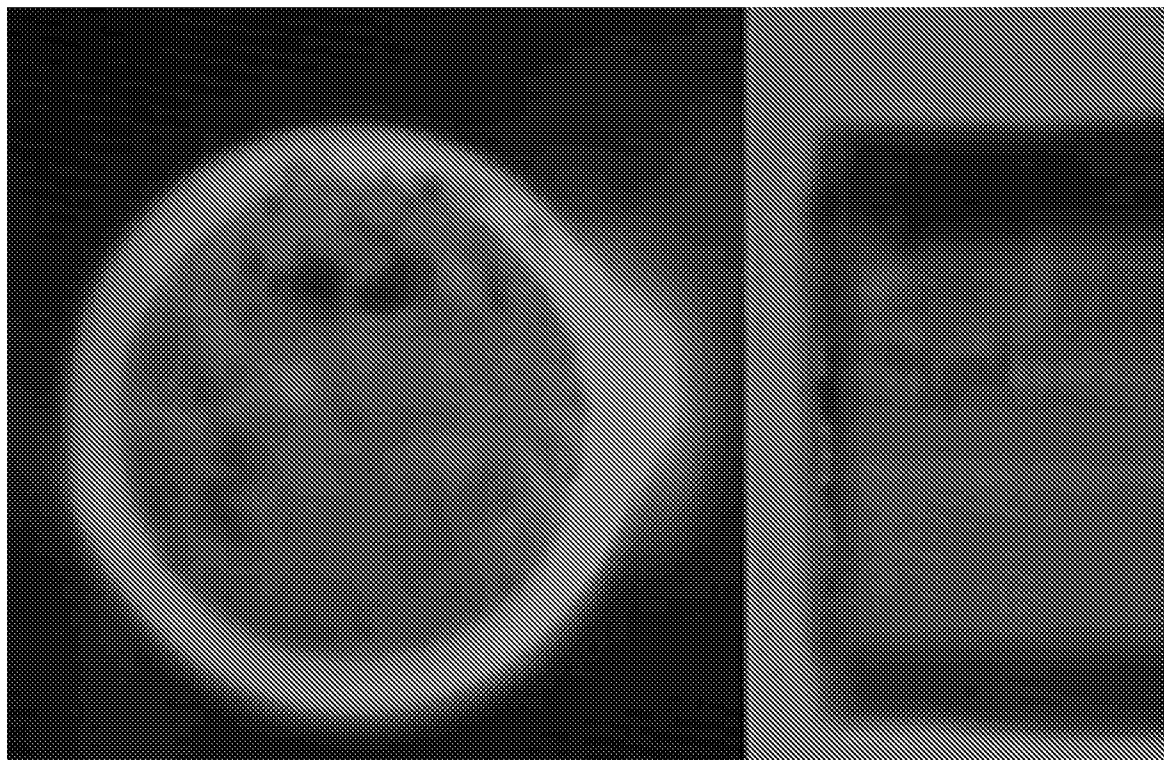


FIG. 8

AFTER 20 MINUTES IN DI WATER (MMF)

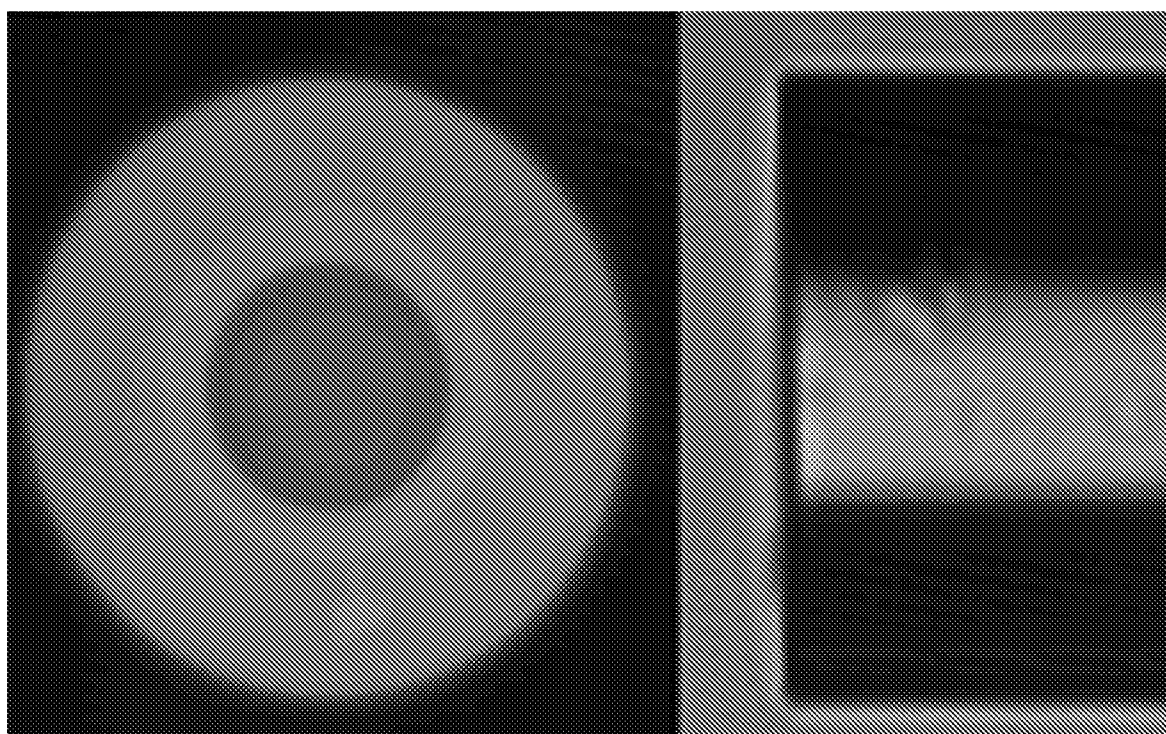


FIG. 9

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AFTER 20 MINUTES IN DI WATER (DCF)

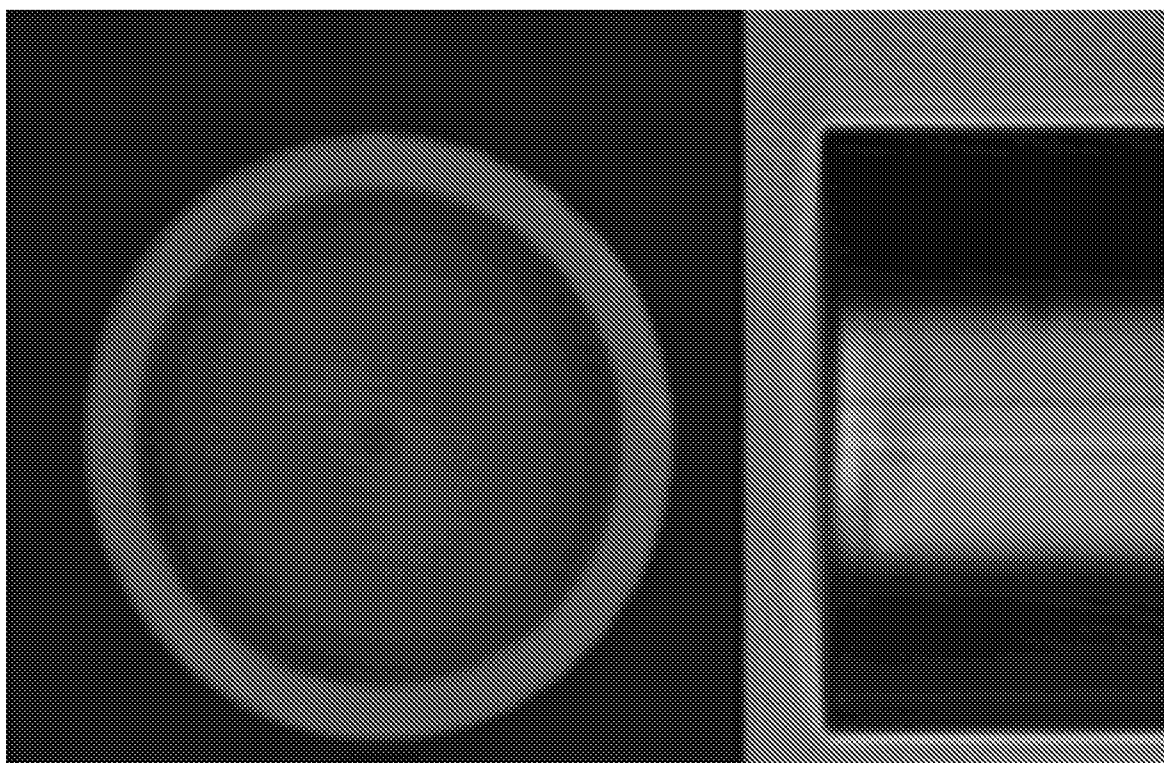


FIG. 10

FIG. 11

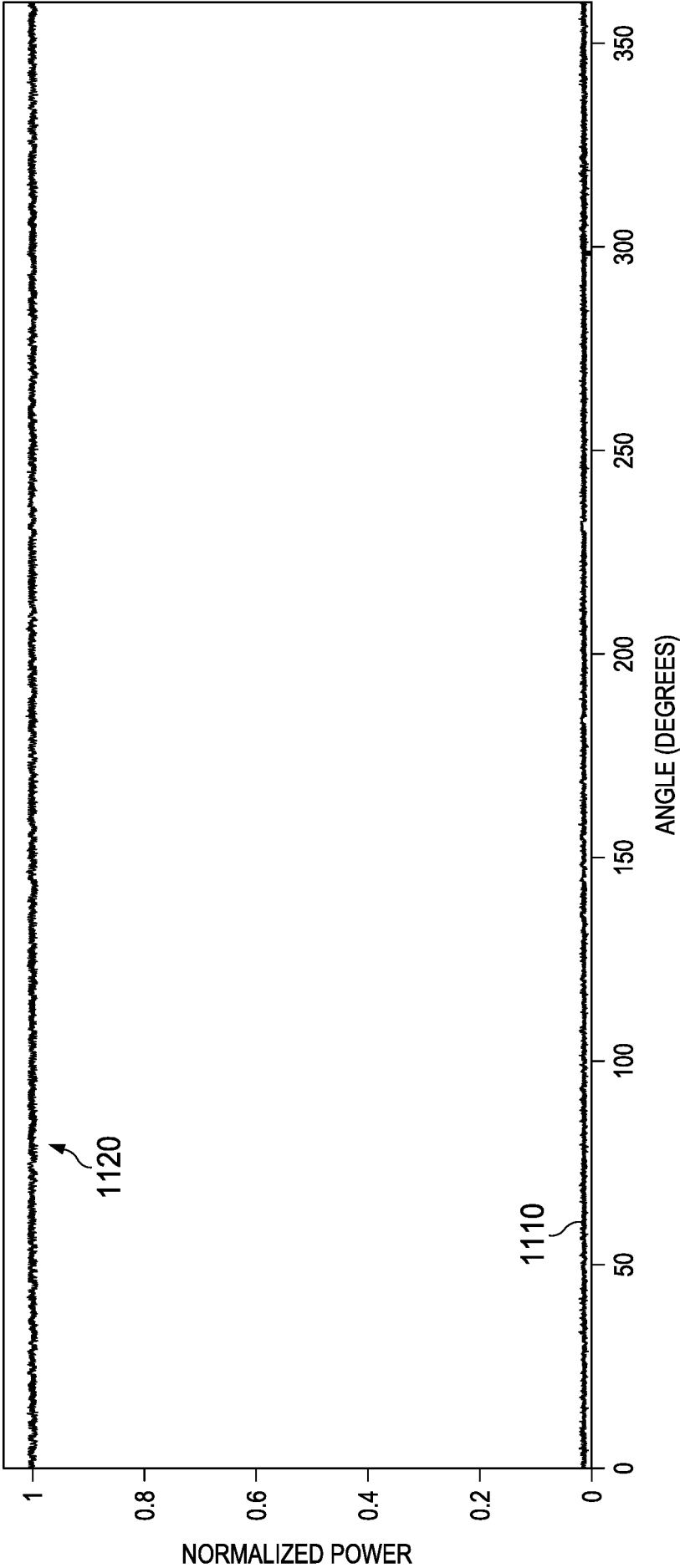


FIG. 12

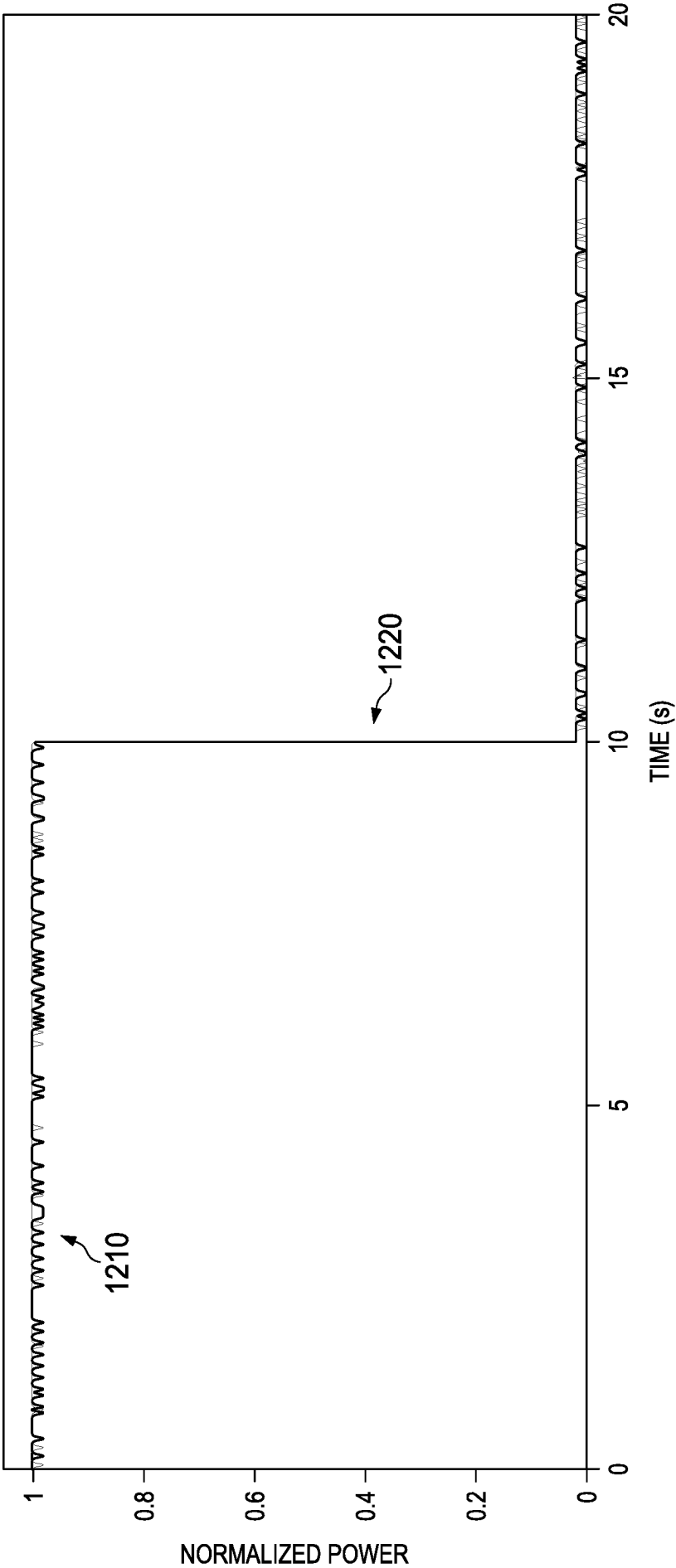
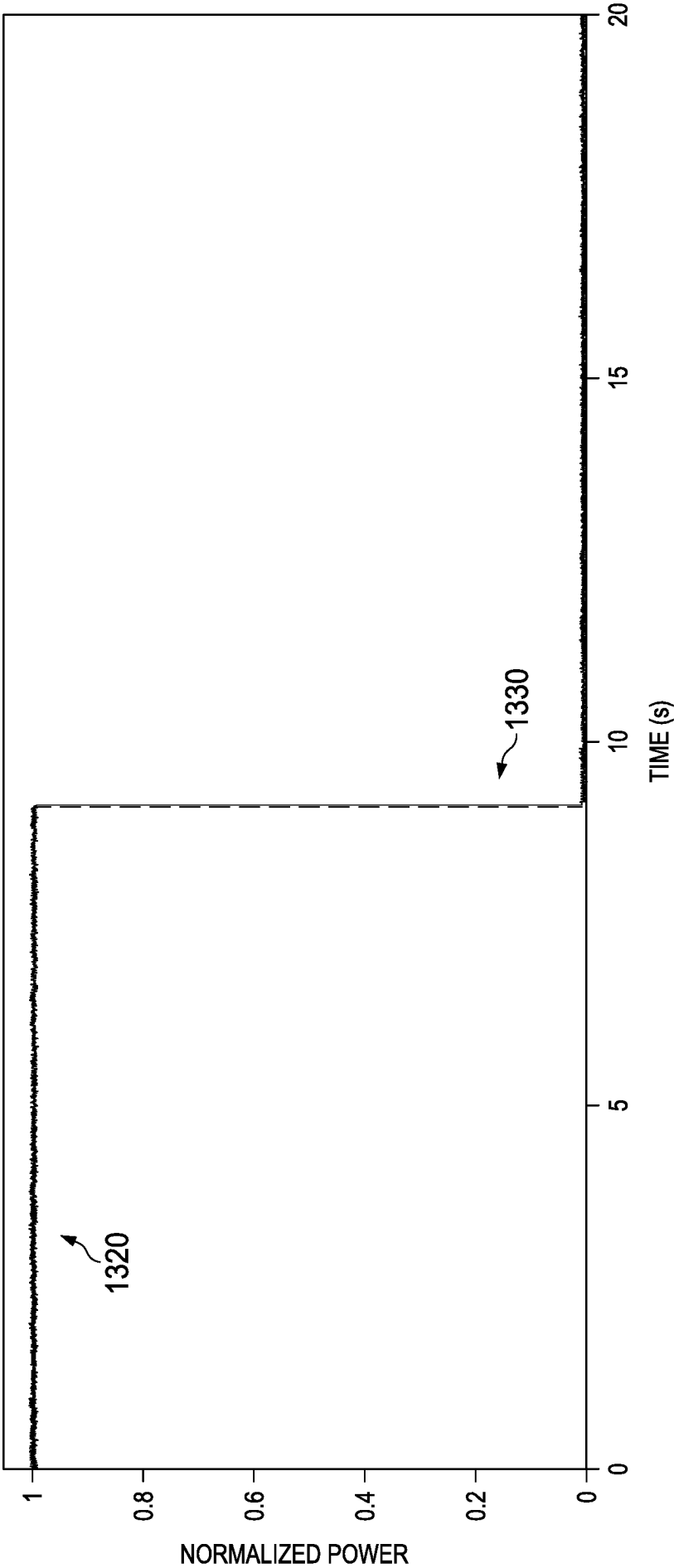


FIG. 13



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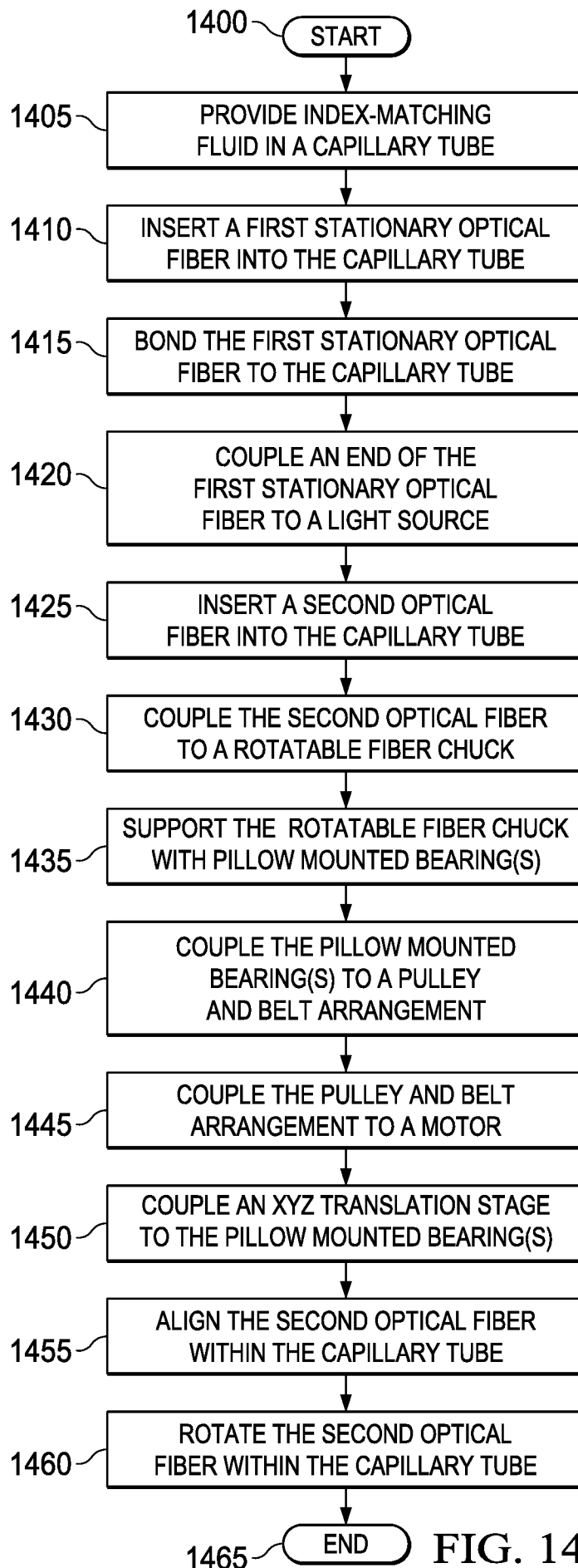


FIG. 14

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2017/021433

A. CLASSIFICATION OF SUBJECT MATTER INV. G02B6/36 A61B1/00 G02B6/26 ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED		
Minimum documentation searched (classification system followed by classification symbols) G02B A61B		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal, WPI Data		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2011/164255 A1 (KONNO KENJI [JP] ET AL) 7 July 2011 (2011-07-07) paragraph [0039] - paragraph [0067] figures 2-6	1-20
X	----- EP 2 437 088 A1 (KONICA MINOLTA OPTO INC [JP]) 4 April 2012 (2012-04-04) paragraph [0031] - paragraph [0054] figures 2, 6, 7, 12	1-20
A	----- JP 2012 228510 A (UNIV TOYOHASHI TECHNOLOGY; HAMAMATSU UNIV SCHOOL OF MEDICINE) 22 November 2012 (2012-11-22) paragraph [0050] paragraph [0062] - paragraph [0069] figures 1-6 ----- -/-	1-20
☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents : "A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 12 May 2017		Date of mailing of the international search report 26/05/2017
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016		Authorized officer Szachowicz, Marta

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2017/021433

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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A	US 2002/039472 A1 (TAKEUTI HIROKAZU [JP] ET AL) 4 April 2002 (2002-04-04) paragraph [0115] paragraph [0123] - paragraph [0127] figure 1 -----	1-20

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