

NASA CASE NO. LAR 15050-1-SB

PRINT FIG. 1

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COLLECTION OF LIGHT FROM AN OPTICAL FIBER WITH A NUMERICAL
APERTURE GREATER THAN ONE

AWARDS ABSTRACT

In an optical fiber having $NA > 1$ light may be internally reflected when it strikes the fiber end at a fiber-air interface. This problem may be overcome by modification of the fiber by reverse tapering the core. Light is redirected by the taper to strike the interface at an angle closer to normal. This allows light to exit the fiber end that would be internally reflected in an untapered fiber of $NA > 1$.

The novelty of the present invention lies in the tapering of the fiber core for increased through transmission of light. Prior art devices have made use of fiber tapers to achieve mode control or fiber coupling. The problem of internal reflection has not been addressed as it is one that is not as important in fibers having $NA < 1$, which are more common. In chemical sensing it is advantageous to make use of fibers having higher NA due to an increased sensitivity. However the advantages in sensitivity are diminished due to the loss of signal at the fiber-air interface. The present invention overcomes the problem of loss at the interface, thus facilitating the use of high NA fibers for chemical sensing.

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Origin of the Invention

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The invention described herein was jointly made by an employee of the United States Government and a contract employee during the performance of work under NASA Contract No. NAS-1-19236. In accordance with 35 U.S.C. 202, the grantee elected not to retain title.

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Background of the Invention

1. Technical Field of the Invention

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The present invention relates generally to the collection of light from optical fibers and specifically to increased efficiency in the collection of light from fibers having a high numerical aperture.

2. Discussion of the Related Art

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Optical fibers may be included in structures to act as chemical sensors. Through use of special materials the fiber may be made to detect the presence of particular chemical species. A coating may be chosen that will fluoresce in the presence of certain chemical species. In this manner, chemical concentration may be monitored in inaccessible portions of the structure without requiring that the structure be dismantled. If the chemical species are chosen to correspond to those that are expected to result from corrosion of the structure, corrosion may be monitored.

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In general, fibers used for this purpose have a numerical aperture (NA) of less than one. NA is defined by equation 1:

$$NA = (n_1^2 - n_2^2)^{1/2} / n_1, \quad (1)$$

where n_1 is the index of refraction of the fiber core and n_2 is the index of refraction of the cladding. The critical angle, θ_c , of a fiber is the angle at which light traveling in the fiber core may strike the core/cladding interface and still be totally internally reflected and thereby propagated down the fiber. Light striking the core/cladding interface at an angle smaller than the critical angle will refract through the interface into the cladding and be lost.

10 In a fiber of $NA < 1$, where the fiber end is in air, light that propagates down the fiber at close to the critical angle of the fiber will refract through the end of the fiber into the surrounding air, where it may be detected. However in a fiber of $NA > 1$, such as a sapphire fiber, light traveling at close to the critical angle will be internally reflected at the endface of the

15 fiber if the fiber is in air. Thus, use of a fiber with $NA > 1$ results in a portion of the signal being lost due to total internal reflection at the end face of the fiber. The disadvantage of using fibers with $NA < 1$ is that they are not as sensitive as fibers with $NA > 1$, that is, the theoretical signal produced in a system employing fibers with $NA > 1$ would be stronger than

20 that produced by a system using fibers with $NA < 1$ if the problem of reflection at the air interface could be overcome.

To overcome the problem of total internal reflection, several solutions have been suggested. The amount of light transmitted through the endface of the fiber is dependant on n_0 , the index of refraction of the surrounding

25 medium. By altering n_0 one may allow more light to escape and be available for detection. This may be achieved by the use of a graded index lens at the fiber end or index matching fluids or gels. Another option is to provide a fiber having a varying index of refraction in a region near the fiber end. Alternatively, the fiber end may be hemispherically shaped to change

the angle of incidence of light rays striking the fiber end. Each of these methods have limitations, both in implementation and on the amount of light that they may untrap.

It is known that tapering of optical fibers may be employed to alter
5 the path traveled by the light that propagates down the fiber. Barnoski, et. al. (U.S. 4,060,308, herein incorporated by reference) make use of a taper in an optical fiber to control which modes of propagation are excited in the core of an optical fiber when a laser beam impinges on the fiber. By changing the angle at which the laser impinges the fiber, the mode may be
10 selected. In addition, the reverse holds true, that is, by placing a detector at a particular angle, a particular mode may be selected to be detected.

Another use of fiber tapering is in coupling fibers to other fibers. Darbon, et. al. (U.S. 5,337,380, herein incorporated by reference) make use of a taper to couple two fibers having differing core diameters. Murphy, et.
15 al. (U.S. 5,216,731, herein incorporated by reference) fuses and draws to a taper several fibers to couple multiple fibers in a bundle.

Summary of the Invention

20 It is an object of the present invention to provide an optical fiber having $NA > 1$ that has improved characteristics for through transmission of light at a fiber-air interface by reducing the problem of total internal reflection at the fiber end.

It is a further object of the present invention to make use of such a
25 fiber in chemical sensing.

To achieve the forgoing objects a fiber is employed that has a reverse tapering of the core at one or both ends. The reverse tapering allows an increased portion of the light traveling through the fiber to escape the fiber

end by increasing the angle at which light strikes the interface so that the light strikes the interface at an angle closer to the normal angle.

For chemical detection, the fiber is coated with a material that fluoresces in the presence of preselected chemical species. At least one
5 end of the fiber is reverse tapered and is positioned so that light refracting through the end will impinge on a photodetector indicating the presence of the preselected chemical species.

Brief Description of the Drawings

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Fig. 1 is a drawing showing a fiber having $NA < 1$. A representative light path is shown traveling at approximately the critical angle in the fiber and refracting out of the end of the fiber.

Fig. 2 is a drawing showing a fiber having $NA > 1$. A representative
15 light path is shown traveling at approximately the critical angle in the fiber and being reflected at the endface of the fiber.

Fig. 3 is a drawing showing a fiber having $NA > 1$ and a reversed tapered end. Further it shows a light beam traveling out of the end of the fiber. The path of the beam in a fiber without a reverse tapered end is
20 shown for comparison.

Description of Preferred Embodiments

An optical fiber having $NA < 1$ is shown in Fig. 1, the view is
25 through the center line of the fiber, along its length. The fiber consists of a core 10, surrounded by a cladding 12. At one end of the fiber is shown an interface 14 between the fiber and air. A representative light ray 16 is shown. This light ray is propagating along the length of the fiber, in the core 10, and strikes the cladding 12 at an angle θ_c , the critical angle of the

fiber. Light traveling at close to the critical angle will strike the interface **14** at an angle γ_1 and refract through into the air, leaving at an angle γ_2 .

Fig. 2 represents an optical fiber having $NA > 1$. Otherwise the fiber of Fig. 2 is similar to the fiber of Fig. 1. The fiber, shown in cutaway, has a core **10** that is surrounded by a cladding **12**. At one end of the fiber an interface **14** between the fiber and air is shown. A representative light ray **16** is shown propagating along the length of the fiber, in the core **10**, and striking the cladding at an angle θ_c , the critical angle of the fiber. In this case, light traveling at close to the critical angle will strike the interface **14**, and be totally internally reflected, remaining in the fiber core **10**. Light rays traveling at greater angles, and therefore striking the interface at angles closer to the normal angle will refract through the interface.

The operation of the present invention is shown in Fig. 3. As in Figs. 1 and 2, the fiber is shown in cutaway, along its length. The fiber has a core **10** surrounded by a cladding **12**. At one end of the fiber an interface **14** between the fiber and air is shown. A representative light ray **16** is shown propagating along the length of the fiber, in the core **10**. The light ray strikes the core cladding interface at a propagating angle, θ . Near to the interface the core has a reverse taper **20**, and thus has a larger diameter at the interface than along its length. The core is tapered at an angle α , defined as the angle between the tapered portion of the core and a line normal to the interface. As the light ray **16** strikes the taper **20** at **18** it is redirected along path **22**, striking the interface at an angle, ϵ , and refracting through. After exiting the fiber it may be detected by detector **24**. The dashed lines represent the path **26** of a light ray in a fiber lacking taper **20** and correspond to the light path of totally internally reflected light as was shown in Fig. 2.

The optimum angle of taper α is dependant on n_1 and n_0 , the index of refraction of the core and medium, respectively. The optimum value of α is found from the following inequality:

$$0 < \sin \epsilon < (n_0/n_1) \quad (2)$$

5 where:

$$\epsilon = (\pi/2 - \theta) \text{ when } (\pi/2 - \theta) \leq \alpha \quad (3)$$

and,

$$\epsilon = 2\alpha - (\pi/2 - \theta) \text{ when } (\pi/2 - \theta) > \alpha \quad (4)$$

and,

$$10 \quad \theta_c \leq \theta < \pi/2. \quad (5)$$

Egalon and Rogowski (US app ser. no. 08/_____, filed _____, herein incorporated by reference) gives a further discussion of the derivation of equations 2-4.

Another embodiment of the present invention makes use of a curved
15 reverse taper.

One application of a fiber having a reverse tapered core lies in the detection of chemical species. A fiber may be coated with a sensitive fluorescent substance, that is, in the presence of chemical species to which the substance is sensitive, it will fluoresce. The light so produced will be
20 injected into the fiber and propagate in the fiber, primarily in the fiber core. A detector aligned with the end of the fiber will detect this light indicating the presence of the chemical species within. This type of device may be used to interrogate the interior of structures for particular chemical species without dismantling the structure. A structure may be built to include such
25 sensors. For example, in an aluminum aircraft lap joint a fiber may be included that is coated with Morin hydrate, a sensitive substance that fluoresces in the presence of aluminum ions, a product of the corrosion of aluminum. As the aluminum corrodes, producing aluminum ions, the Morin

hydrate will fluoresce, producing a light signal that may be detected at the end of the fiber.

In a manner similar to the detection of chemical species temperatures may be monitored. In lieu of a coating sensitive to chemical species a
5 coating may be applied that is sensitive to temperature.

Other applications and modifications of the present invention will be apparent to those skilled in the art. The above embodiments are not exhaustive but rather given by way of example. It is understood that the present invention is capable of numerous modifications within the scope of
10 the following claims.

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Abstract of the Disclosure

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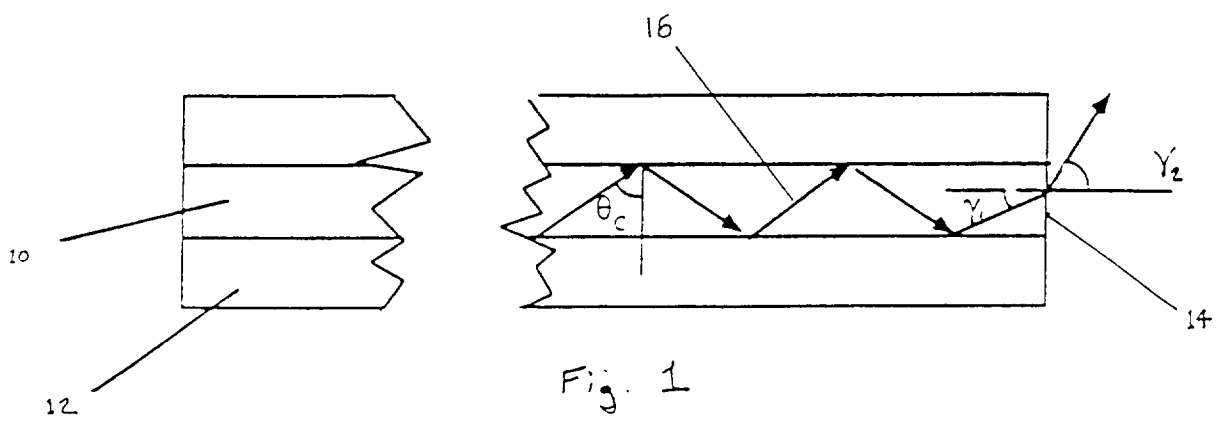
In a fiber having $NA > 1$, in air, a large portion of light reaching the fiber end is totally internally reflected instead of escaping at the endface of the fiber. In the present invention a reverse taper is introduced at the end of the fiber to alter the light path so that more of the light in the fiber may escape to be collected by a detector. In chemical sensors, fibers having $NA > 1$ are desirable due to increased sensitivity. An application of the present invention is to allow the use of fibers having $NA > 1$ in chemical sensors. Fiber sensors may further be embedded into a structure so that corrosion may be monitored without destruction or dismantling of the structure.

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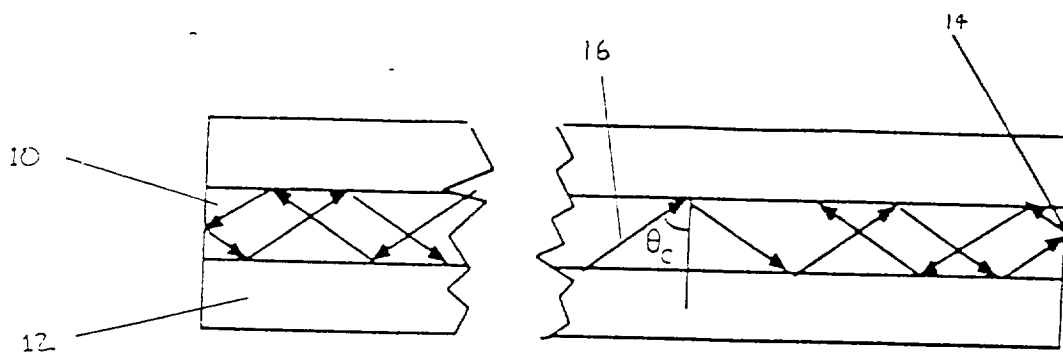


Fig. 2

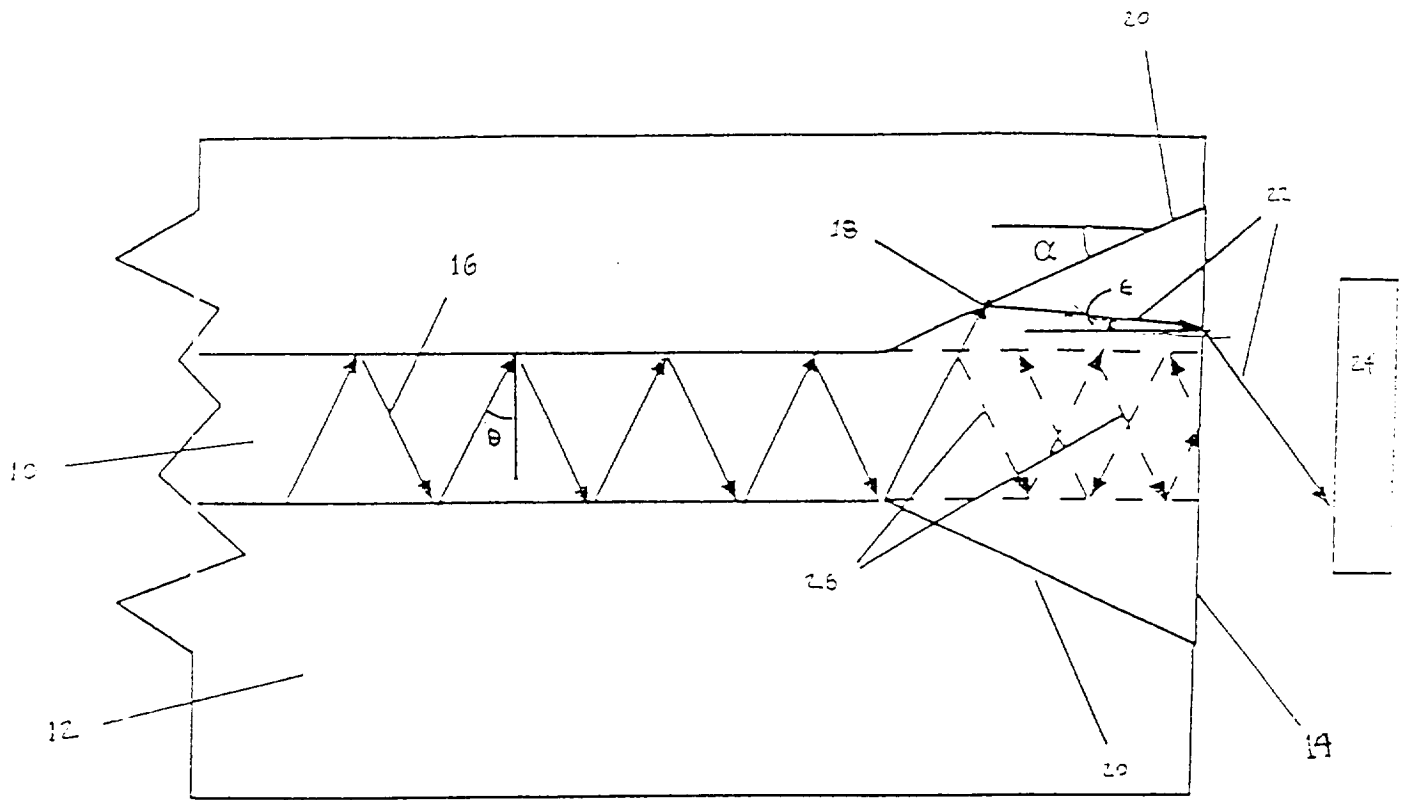


Fig. 3