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POF Sensor Design Using Milled Annular Cavities

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Abstract: We present the design for a POF sensor with two annular cavities milled into the fiber and subsequently filled by a photoluminescent gel. We show that an optimal separation exists for maximum photoluminescent signal.

OCIS codes: 060.2290 (Fiber materials), 060.2370 (Fiber optics sensors), 130.5460 (Polymer waveguides), 160.5470 (Polymers)

1. Introduction

Polymer Optical Fiber (POF) sensors have been developed with several applications in mind over the years, and by many different functionalization strategies. Notable examples are Fiber Bragg Grating (FBG) sensors, which can be used for measurement of strain/force [1, 2], temperature [3], humidity [4], pH [5] and more. They continue to be an active field of research with many promising application areas. Early examples of fiber optical probes are the pH and oxygen probes made by Peterson [6, 7], based on absorption and photoluminescence respectively, and later developments by Wolfbeis [8], using fluorescence decay time as an indicator of oxygen concentration.

Placing photoluminescent compounds at the tip of the fiber is an easy and simple method for creating a photoluminescence sensor. The conditions important for the sensor performance are the matrix in which the compound is embedded, and the sensitivity of the compound itself to the measurand of interest. Other designs exist for photoluminescent sensors, for example one can embed the photoluminescent compounds in the cladding of the fiber by suitable methods [9, 10] and in that way functionalize the fiber for photoluminescent sensing.

When designing POF sensors for photoluminescent sensing, one of the first issues is that the design must generate enough photoluminescence emission for the detection setup to function properly. Engineering and manufacturing a good a detector can do much for the sensor, and increasing input power in certain situations will also help – but at the fundamental level, the sensor element itself is the limiting factor. Applying a photoluminescent film to the tip of a fiber is a relatively easy task, and it is a quick way of manufacturing a sensor. However, if the sensing mechanism is not supposed to be at the tip of the fiber, but at some position along the length of the fiber, another design is needed.

In the following, we introduce a sensor design, which is easy to fabricate, and has great potential for having photoluminescent sensors along the length of the fiber.

2. Sensor

The sensor design is based upon two annular cavities milled into the fiber core. The cavities are separated by a distance, s, and are milled a depth, d, into the fiber. The length of the cavities is l. These parameters are shown in fig. 1. The response strength is dependent on all three geometrical parameters. Interestingly, the design shows an optimal separation, for which the photoluminescent response is greatest.

2.1. Materials & Equipment

Polymer Optical Fiber is a 1 mm PMMA core fiber with fluorinated polymer cladding (ESKA CK-40). The milling of the fiber was performed using a Proxxon MICRO Mill MF 70. Photoluminescence spectra was measured using an Ocean Optics HR-2000 spectrometer.

Chemicals used are acetone and trichloroethylene, for creating a mixed solvent for PMMA. The photoluminescent compound used was PtOEP (Platinum Octaethylporphyrin) and was acquired from Sigma Aldritch.

2.2. Fabrication

The fiber samples were fabricated by first cutting pieces of the bare fiber spool into pieces of 20 cm to 30 cm. Next, the samples were milled using a suitable milling head with the Proxxon machine. After milling the samples were placed in an environmental chamber and annealed for at least 16 hours at 90 degC and 90 % humidity, to remove residual stresses in the fibers.

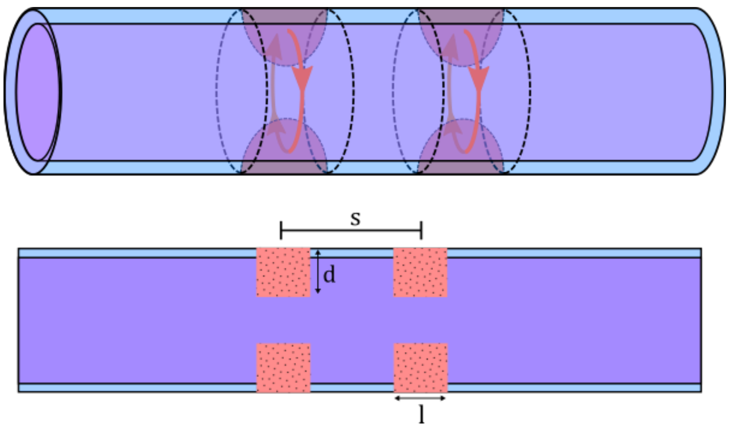

Fig. 1. The photoluminescent sensor design. Two cavities are milled with a central separation of *s*. The cavities are subsequently filled with a mixture of PMMA, solvent and PtOEP. As the solvent evaporates it leaves a hardened volume of PMMA and PtOEP.

With the annealing done, the milled trenches are filled with a solution of PMMA, PtOEP and solvent. The solution is a 15 % (w/w) solution of PMMA and solvent, and with PtOEP added such that the molar concentration is 0.77 mM. The solvent used is a 1:3 mixture of acetone and trichloroethylene. After application to the milled trenches the solution is left to dry for 24 hours, after which the samples are measured in the experimental setup.

In two separate experiments, batches with varying separations were created. In the first experiment we fabricated 10 fibers with a single cavity, 10 fibers with 1 mm separation and 9 fibers with 10 mm separation. In the second experiment we made 10 fibers with a single cavity, 10 fibers with 2 mm separation, 10 fibers with 10 mm separation and 10 fibers with 15 mm separation.

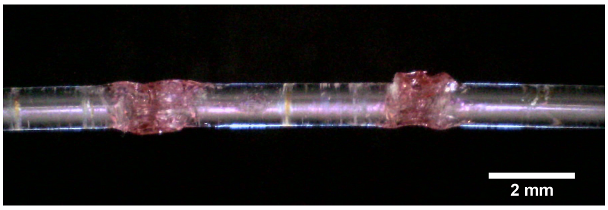

Fig. 2. Example of fiber with two annular cavities milled into the core and subsequently filled with a photolumiscent gel.

3. Results & Discussion

For each of the two experimental runs, the photoluminescence response of the dual cavity fibers were compared to the response from the average of the single cavity fibers within that particular experiment. This way, we could compare the photoluminescence response in terms of how much gain we achieve in the photoluminescence signal, by adding a second cavity with a separation of *s*. The results could then be compared across the two experiments, as a means of verifying the results. In fig. 3, the average photoluminescence spectra from the experiments for each separation are shown, as well as a plot of the peak intensity as a function of separation distance. The y-values are the relative intensity compared to the single cavity.

The key insights from the results are that there is a pronounced difference in the photoluminescence response depending on the separation between the cavities. A gain of up to 50 % can be achieved by placing the second cavity a distance of 2 mm from the first cavity. Placing it closer or farther away diminishes the gain from the second cavity.

The explanation of the results is probably found by considering the shadowing effect created by the first cavity. From certain angular directions the cavity blocks excitation light from reaching the second cavity, and the photoluminescence emitted from the second cavity is similarly blocked by the first cavity. As the separation is increased, this shadow changes and the response varies.

As the fiber is a large multimode fiber of 1 mm diameter, and the cavities are large compared to the wavelengths of both excitation and emission, the problem of analyzing the behaviour can be done using geometrical optics. As

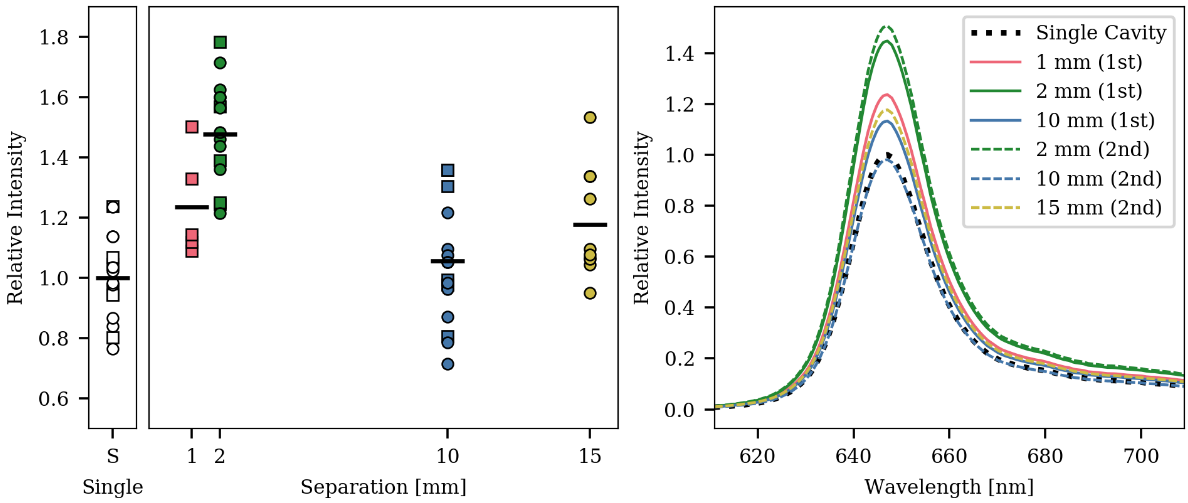

Fig. 3. Results from measuring photoluminescent response from the various samples. The leftmost plot shows the photoluminescent response of a single cavity, relative to the average. The middle plot depicts the photoluminescent response of a dual cavity with a given separation, also relative to the average of a single cavity. The black lines is the average response. The square markers are the results from each individual fiber for the first experiment containing dual cavities with separations of 1, 2 and 10 millimeters. The circle markers are the results from the second experiment with separations of 2, 10 and 15 millimeters. To the right are the average fitted spectra for each of the 7 different batches measured. These have also been normalized to the peak intensity of the single cavity fibers.

a first approximation we can consider only the meridional rays in the fiber.

In fig. 4, A, B and C are points of particular interest for the analysis. In the given picture, the angle span from which rays can reach and exit point B is shown. If the second cavity is moved further away, this span will decrease. Similarly, one can draw the angle span for the point A. It's important to factor in the maximum propagation angle of the rays inside the fiber. The angles considered can only be up until some angle θ_c which is the complementary angle to to critical angle of the core-cladding interface. Rays with an axial angle larger than θ_c will not be totally internally reflected, and can thus be ignored.

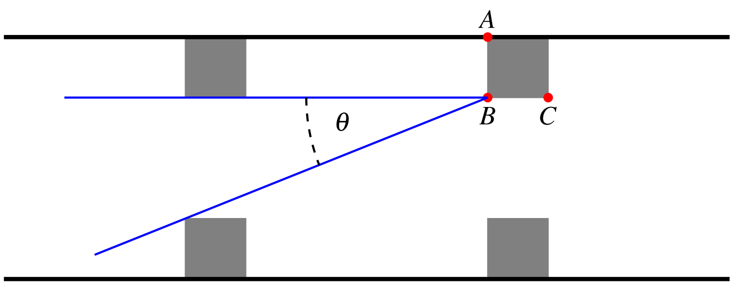

Fig. 4. Meridional ray analysis of the cavities. Some rays are blocked from reaching the surface spanned by points A and B, as well as the surface spanned by B and C. As the separation changes, the angular span which has acesss to a given point changes.

As the separation between the cavities is changed, the relationship between the angle spans from which light has access to and from the second cavity, changes. If the cavities are very close together, the surface between A and B will be in total shadow and and will therefore not contribute to the photoluminescent response. Increasing the distance will see more and more light reach the surface, but at some point the rays will once again be blocked. Moving the cavities further away will see the shadows increasing and decreasing in a complex fashion.

Apart from the effect of the shadow created by the first cavity, other effects may be important such as the power in skew rays and reflections of light, coming from the second cavity, on the horizontal surface of the first cavity. The reflections will have to be described by a suitable surface model, which will neither be totally lambertian nor specular due to surface roughness. The differences in refractive index of the core and sensing cavities may also have effects in the response.

4. Conclusion

We have presented results on a POF sensor design using two milled annular cavities. The results show that an optimal separation of the cavities exist, for which the photoluminescent response is greatest. The results will be important to the fabrication of optimal photoluminescent POF sensors, and may pave the wave for designs of multipoint photolumiescent POF sensors.

Further work will need to be conducted in order to fully understand the relationship between the geometry of the cavities and the photoluminescent response. Understanding this relationship will give insights into optimal design geometries for sensors of this type and will also provide insight into ways in which multipoint sensing can be achieved. In a situation with two sensing points of one or more annular cavities, finding an optimal design which provides enough photoluminescent response from both sensing points onto the detector is not a trivial task, but given a realistic computational model for the photoluminescent response it is plausible.

Acknowledgments

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