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Regular Articles

# Impacts of the distribution of hydrogel spheres attached on bare fiber core on light transmission of the fiber

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ABSTRACT

Impacts of the distribution of hydrogel spheres attached on bare fiber core on fiber transmission are studied by ray-tracing simulation. The aim of the study was to optimize the previously reported configuration and sensitivity of humidity sensors based on bare fiber core attached with humidity-sensitive hydrogel spheres. Four uneven distribution types, namely, asymmetric-geometric, asymmetric-arithmetic, symmetric-geometric and symmetric-arithmetic for sensors in length of 10 cm and attached with six hydrogel spheres are simulated and compared with the uniform distribution. Spheres in diameter of 0.6, 0.8 and 1 mm are simulated to reveal impacts of the sphere size. It is found that the sphere size is a significant factor that determines impacts of the sphere distribution on the sensitivity, which is defined as the slope of fiber transmissions over refractive index of spheres. For sensors attached with 0.6 mm hydrogel spheres, uneven distributions result in sensitivities close to that of the uniform distribution. However, uneven distributions with 0.8 or 1 mm spheres yields much higher sensitivities. The highest sensitivities for sensors with 0.8 and 1 mm are 19% and 39% higher than that of uniform distributions respectively, suggesting that properly distributing hydrogel spheres is a convenient way to enhance sensitivities. Moreover, results show that sensors with 0.8 mm hydrogel spheres have higher sensitivities than that of 1 mm for the same sphere distribution, and the underlining re-collecting effect is revealed to explain this phenomenon. In addition, simulations reveal that optical loss of spheres have a positive but marginal effect on the sensitivity.

## 1. Introduction

The fiber optic humidity sensor is one of the most promising technologies among various humidity sensor types. This sensor is extensively studied due to its enormous variety and distinct advantages including electromagnetic immunity, high precision, excellent durability and distributed sensing ability [1,2]. New humidity sensitive materials and/or new fiber optic sensor designs are reported almost monthly if not weekly. Just last few years have witnessed a great number of brand new fiber optic humidity sensors, like Mach-Zehnder interferometer [3–5], micro resonator [6,7], whispering-gallery-mode resonator [8,9], polymer fiber Bragg gratings [10,11], side polished optical fiber structure coated with gelatin [12] etc. These advanced technologies aim for high precision humidity measurement, but the sensor fabrication process is intricate and of measurement equipments are high-cost. For a low-cost solution, fiber optic humidity sensor based on light intensity modulation is the technology of choice because equipments for measuring light intensity is normally much cheaper than those measuring wavelength [13–15]. For example, we proposed a new type of humidity sensors by curing humidity-sensitive hydrogel spheres on bare fiber core, and found that their sensitivity is much better than the sensor fabricated by coating hydrogel films on bare fiber cores [15]. In that work, we investigated impacts of sphere size and number of spheres on sensor sensitivity, and found that the sensitivity of the sensor increased with the size and number of hydrogel spheres attached. However, simulation and experimental studies in that preliminary study only considered the most basic design that all hydrogel spheres are evenly distributed along the fiber core for simplicity. That is, intervals between adjacent spheres were all the same.

This paper aims to improve the sensitivity of this type of humidity sensors by optimizing the distribution of hydrogel spheres along the fiber core for a specified sensor length and a given number of spheres. To accomplish this objective, ray-tracing simulations are conducted for four major types of uneven distributions, and accordingly obtained sensitivities are compared with the results obtained on uniformly distributed spheres. Besides, hydrogel spheres of different diameters are also compared.

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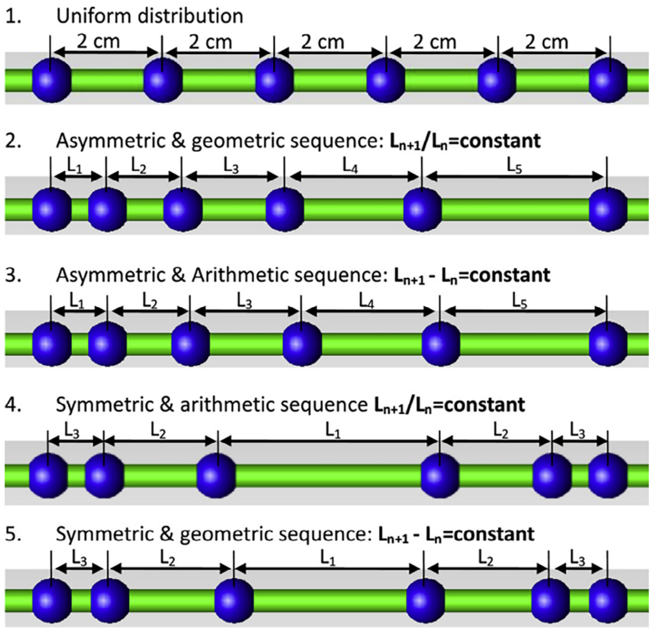


**Fig. 1.** Illustration of the uniform and four uneven distributions of hydrogel spheres in diameter of 0.8 mm along the bare fiber core.

## 2. Simulation

The commercial optical engineering tool – TracePro Expert 7.0.3 (Lambda Research Corporation) is used to run ray-tracing simulation. A fiber with the core in diameter of 400 µm, the cladding in thickness of 15 µm, and in length of 2 m is created, and refractive index of the cladding and the core are set as 1.4000 and 1.4715 respectively, according to the real optical fibers selected for previous experimental studies. In the middle of the fiber, a segment of cladding in length of 20 cm is ripped, and six hydrogel spheres are drawn along the bare core. The length of the sensor part is set to be 10 cm, that is, the distance from the first to the sixth hydrogel spheres is 10 cm. The distribution of hydrogel spheres is investigated to find its influence on the sensor sensitivity. Five major configuration types are investigated, namely, the uniform, asymmetric & geometric (ASY-GEO), asymmetric & arithmetic (ASY-ARI), symmetric & geometric (SYM-GEO), and symmetric & arithmetic (SYM-ARI) distribution, as shown in Fig. 1. The uniform distribution is the base configuration for comparison. For geometric distribution, the configuration parameter is the distance ratio of two adjacent spheres $L_{n+1}/L_n$, while the parameter for arithmetic distribution is the distance increment $L_{n+1} - L_n$, as shown in Fig. 1. Spheres in diameter of 0.6, 0.8 and 1 mm are studied for comparison. The input light is mimicked by the grid source in the software. A number of 817 light rays are uniformly distributed across the fiber core at one end, and the circular pattern is chosen. The largest half angle is set to be 15°, which is calculated from the numerical aperture of the fiber.

For a particular distribution, refractive indices of hydrogel spheres are set to be 1.40, 1.41, 1.42, 1.43, 1.44 and 1.45, and the software performs ray-tracing simulation. The transmission of the sensor is calculated by dividing the intensity of output light over the input light. The sensitivity for this particular distribution is obtained by linearly fitting transmission data and refractive index as shown in Fig. 2. It should be noted here that the sensitivity defined above is actually the sensitivity of the sensor to the refractive index of hydrogel spheres rather than the real sensitivity to the relative humidity surrounding the sensor. However, two sensitivities are positively related since variation of relative humidity surrounding the sensor leads to refractive index change of hydrogel spheres and sensor transmissions, therefore, the optimized sphere distribution also applies to real sensors experimentally.

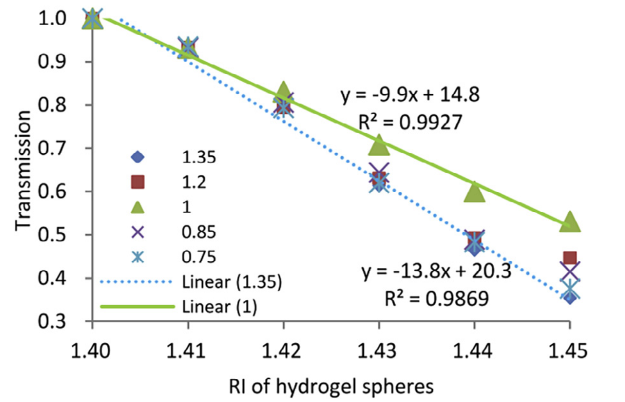


**Fig. 2.** Change of sensor transmissions versus refractive index of hydrogel spheres for five parameters ($L_{n+1}/L_n$) of ASY-GEO, and linear fitting for $L_{n+1}/L_n$ equals to 1 and 1.35 to obtain sensitivities. Sensors are attached with six hydrogel spheres in diameter of 1 mm.

## 3. Results & discussion

Fig. 2 shows the change of fiber transmission for five cases of ASY-GEO distribution. The figure presents the linear fitting and according sensitivities for two configurations, namely, $L_{n+1}/L_n$ of 1 and 1.35. The two coefficients of determination ($R^2$) of fitting are higher than 0.98, suggesting good linearity. It should be noted that the RI range for fitting is from 1.40 to 1.45. Changing the RI range would result in different sensitivity. Experimentally, the range of refractive index will be determined by properties of the humidity sensitive material.

In Fig. 3, plots of sensitivities for the four uneven distributions and its dependence on unevenness parameters are shown. For geometric distribution, $L_{n+1}/L_n$ is changed from 0.75 to 1.35, because two spheres will overlap if it is less than 0.75 or larger than 1.35. The range of $L_{n+1} - L_n$ for arithmetic distribution is from $-0.5$ to 0.5 for the same reason. There are quite a few interesting findings from the four figures.

Firstly, it is found that the relationship between sensitivities and unevenness of sphere distributions highly depends on the sphere diameter. For sensors attached with hydrogel spheres of diameter 0.6 mm, their sensitivities change very slightly, no matter how spheres are distributed. The sensitivity for the uniform distribution is 15.2, while the highest sensitivity among all uneven distributions is 15.5, about 2% higher than that of the uniform distribution. However, for sensors with spheres of diameter 0.8 or 1.0 mm, uniform distribution results in the lowest sensitivity and their sensitivities strongly depends on the unevenness. The sensitivities of uniform distributions are 13.3 and 9.90 for 0.8 and 1 mm spheres, respectively. All the other configurations yield higher sensitivities than that of the uniform distribution. For sensors with spheres in diameter of 0.8 mm, the highest sensitivity is 15.8 with ASY-ARI distribution while $L_{n+1} - L_n$ equals to $-0.4$, which is 19% higher than that of uniform distribution and is also the highest sensitivity achieved among all simulated cases in the present study. The sensor with ASY-GEO distribution while $L_{n+1}/L_n$ equals to 1.4 yields highest sensitivity 13.8 for 1 mm spheres, which is 39% higher than that of the uniform distribution.

Secondly, for sensors with spheres of diameter 0.8 and 1 mm, their sensitivities mainly increase as the distribution of hydrogels spheres are more asymmetric but the increase is not monotonic. The trend is more evident for two asymmetric distributions.

Thirdly, for all simulated cases, sensors with hydrogel spheres of diameter of 0.8 mm have higher sensitivity than that of 1 mm diameter spheres for the same distribution. This seems contradict to the results of previous simulation, in which the larger the hydrogel sphere the higher