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PROPAGATION OF UV RADIATION THROUGH META-MATERIALS AND ITS APPLICATION IN BIO DECONTAMINATION

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Abstract. In this paper we present a method of decontamination using microspheres and fiber optics structures with various geometries. The proposed method consists in the decontamination process at the contact surface irradiated by ultraviolet (UV) radiation during the propagation of the liquid contaminated with viruses and bacteria through the space region created between the microspheres (or fiber system). The increasing of surface contact zone irradiated by UV in such type of system strongly depends on the refractive index of metamaterial and optical properties of viruses or bacterias from the liquid. The complementary effect of decontamination depends on the evanescent zone created at interface of liquid and trapped microspheres from considered structures. In this case, during the propagation of UV wave through microspheres, a tendency of viruses decontamination along the surface system becomes possible.

1. INTRODUCTION

The efficient decontamination methods using the surface of evanescent zone of meta-materials open a new perspective for applications as well as fundamental investigations. It is known that Xenon flash lamps have an emission spectrum rage between ultraviolet and infrared light. The UV-C part of the spectrum is the most important for microbial inactivation [1]. As was observed the inactivation of microorganisms (Bacillus cereus, Listeria monocytogenes, Staphylococcus aureus, Escherichia coli, Salmonella Enteriditis, Pseudomonas aureginosa, and Saccharomyces cerevisiae) can be realised at 5-6 log CFU/plate using a high UV flash, whereas with low UV light only 1-2 log CFU/plate was achieved. Using a monochromator, the authors of Ref. [2] determined the germicidal efficiency against E. coli as a function of wavelength over the range 230-360 nm using about 6 mJ/cm^2. The results showed a maximum inactivation around 270 nm, and no measurable inactivation was observed to occur above 300 nm. Furthermore, the authors concluded that the rich UV content from 220 to 290 nm in the UV spectrum provides the major contribution to inactivation, whichever type of UV source is used.

Considerable research has been performed on the mechanism of microbial inactivation by light pulses. The lethal action of PL (pulsed light) can be due to a photo-thermal and/or a photochemical mechanism. It is possible that both mechanisms coexist, and the relative importance of each one would depend on the fluidity of target microorganism. Most of the authors explain their results based on the photochemical effect. For example, since Ref. [2] achieved inactivation with less than 1 C rise in temperature, they concluded that the lethality can be attributed to the photochemical action of the shorter UV wavelengths. The mechanism of microbial inactivation by PL is frequently explained based on studies using CW UV, in which the inactivation is photochemical. Although the mechanism of inactivation by PL can have similarities with that of CW UV, some differences might exist. The germicidal effect of UV light on bacteria is primarily due to the formation of pyrimidine dimmers, mainly thymine dimmers [3, 4]. The dimmer inhibits the formation of new DNA chains in the process of cell replication, thus resulting in the inactivation (inability to replicate, called clonogenic death) of affected microorganisms by UV [5]. On bacterial spores, UV-C treatment results mainly in the formation of the "spore photoproduct" 5-thyminyl-5,6-dihydrothymine, and in single-strand breaks, double-strand breaks and cyclobutane pyrimidine dimmers [6]. Comparing the wavelength sensitivity for E. coli inactivation with previously reported absorption spectra of the purine and pyrimidine bases of DNA, Wang *et al.* [2] supported the hypothesis that the photochemical effect produced as a consequence of the UV absorption by DNA is the major cause of microorganism inactivation by PL. Application of UV radiation for decontamination of surfaces by viruses and bacteria requires an urgent and effective method of interaction of radiation with microorganisms described above. Open surfaces can't give us the expected result in this area. Let us analyze the surfaces that can appear in the dispersive optical dispositive like photon crystals or systems of fiber optics connected between them through evanescent field [7]. If optical fibers are separated, then this surface consists of fiber length multiplied to the length of the base perimeter. These surfaces per volume increase if such optical systems are arranged in the periodical optical structures with good optical contacts between them. In this situation we must get supplementary surface and good distribution of UV radiation through all volume. We can construct the periodical optical structures with large free spaces between the elements and good evanescent zone necessary for the decontamination of gas or liquid which will flow near this surface. In this case we must estimate the adherence of the liquid to this surface, the penetration distance of the evanescent field in the liquid, absorption of UV pulses by the bacteria and other microorganisms from this contaminated liquid.

The above proposed method to increase the surfaces can be used in hight absorbed liquid or gas. In case when the transparency of the gas or the liquid is large and the UV radiation can penetrate all length of the fibre, we can use the holey fibers, as represented by red circles in Fig. 1a. A photonic crystal fiber is called holey fiber, hole-assisted fiber, microstructure fiber, or microstructured fiber is an optical fiber when gets its waveguide properties not from a spatially varying glass composition, but from an arrangement of very tiny and closely spaced air holes which go through the whole length of fiber. Indeed, the decontamination possibilities of these large volume increase when the contaminated liquid or gas flowing through such a structure. Such air holes can be obtained by using preformed (larger) holes made by stacking capillary or solid tubes (stacked tube technique) and inserting them into a larger tube. Usually, this preform is first drawn to a cane with a diameter of 1 mm, and then into a fiber with the final diameter of 125 μm. Particularly soft glasses and polymers (plastics) allow also the fabrication of performs for photonic crystal fibers by extrusion [8, 9]. There is a great variety of holes arrangements, leading to PCFs with very different properties. All these PCFs can be considered as special fibers. The cooperative phenomena in absorption and radiation of UV pulses in micro cavities [10] of PC by the purine and pyrimidine bases of DNA of toxic bacteria will be in the center of attention in the decontamination regime.

2. ESTIMATION OF DECONTAMINATION VOLUME FOR DIFFERENT METAMATERIALS

Let's start from classical method of decontamination of liquids using UV pulsed light. If we have an cylinder with contaminated liquid and this cylinder is irradiated from all direction (see Fig. 1), the decontamination surface is $S = 2\pi R(h+r)$, where first term indicate the lateral surface and last term represents the surface of bases, R represents the radius of base, h the height of cylinder. If the liquid is not soo transparent, then the penetration depth of UV radiation in liquid is about λ, where λ represents the wavelength of UV light. In this situation, the decontamination volume of liquid

$$V_{classic} \simeq \lambda S = 2\pi R(h+R)\lambda. \tag{1}$$

So, if we use a classical method of decontamination, a big volume of infected liquid remain contaminated $V = \pi R[Rh - 2(h+R)\lambda] \gg V_{classic}$. Bellow we propose the method of decontamination using metamaterials for increasing of decontamination surface.

Sensing properties are expected to be related to nanoscale system dimensions and depend on variable composition at nanoscale level. Let us firstly estimate the

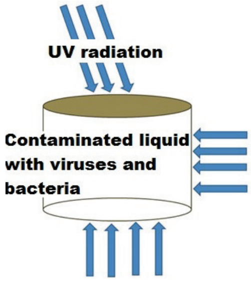

Fig. 1 – Classic decontamination.

contact surface of flowing gas or liquid. In order to increase the contact surface of the contaminated liquid it is proposed to study the propagation of UV radiation through the photonic-crystal fiber (PCF) and photonic crystals (see Figs. 1(a, b) and c), transparent for UV spectrum.

If we consider a PCF placed in a cylinder with contaminated liquid (see Fig. 2 case (a)), the liquid will fill all the space between the fibers. The decontamination surface increase substantially

$$S_{PCF} = \pi(R^2 + 2rhN), \tag{2}$$

where N is the number of fibers from PCF, last term represents the lateral surface of fibers. Here it is considered but only thelateral surfaces of cylinder is irradiated with UV light. The penetration depth of UV radiation (evanescent field) depends only on the relative refractive index:

$$I = I_0 \exp[-z/d], \tag{3}$$

where I is the intensity of UV light of evanescent zone at distance z from fiber, d is characteristic exponential decay depth

$$d = \frac{\lambda}{4\pi n_2}\sqrt{\frac{\sin^2(\theta_c)}{\sin^2(\theta) - \sin^2(\theta_c)}}. \tag{4}$$

Here θ_c represents the critical angle of incidence $\theta_c = \sin^{-1}(n_2/n_1)$; θ is the angle of incidence, $\theta > \theta_c$; n_1 is refractive index of the fibers; n_2 is refractive index of the liquid medium. Lets find the connection with classical method of decontamination. For this we need to express the decontamination aria through the number of fibers. The estimations shows that small radius of fiber r is proportional to $r \sim R/\sqrt{N}$. If we introduce the expression for r in relation (2), it is easy to obtain the following expression for decontamination aria

$$S_{PCF} \sim 2\pi Rh\sqrt{N}. \tag{5}$$

Here we observe that the decontamination surface is proportional to the square

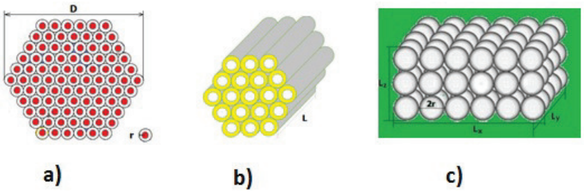

Fig. 2 – Metamaterials for decontamination.

root from the number of fibers. In relation (5) is neglected the small surfaces of cylinder base in comparison with lateral surface of fibers. From relations (3) and (5) results that the decontamination volume of liquid in this case is

$$V_{PCF} \sim 2\pi Rh\lambda\sqrt{N}. \tag{6}$$

Now, it is not difficult to see that the increasing of decontamination volume is proportional to $\sqrt{N}(V_{PCF}/V classic \sim \sqrt{N}$, if only the lateral surfaces of cylinder is irradiated with UV radiation).

Using a same method, we have estimated the surfaces of decontamination using a metamaterial like photonic crystal (see Fig. 2 (c))

$$S_{PC} = 4\pi r^2 N \sim \pi L^2 N^{1/3},$$

where L is the length of cube, r is the radius of one microsphere, N is the number of micro-spheres in metamaterial. The liquid will fill all space between microspheres. The decontamination volume can be expressed through the aria in following form

$$V_{PC} \sim \lambda S_{PC} = \pi\lambda L^2 N^{1/3}. \tag{7}$$

In conclusions we can say that the increasing of decontamination volume depends on the number of micro-spheres as function of $N^{1/3}$ ($V_{PC}/V_{classic} \sim \frac{\pi}{6}N^{1/3}$, if all surface of cube is irradiated with UV). Although at first glance it appears as volume is lower than in PCF case, this is only an illusion. Due to the fact that number of microspheres in metamaterial like photonic crystal is much larger than the number of fibers in PCF, the decontamination volume in second case in much higher. Other priority of last metamaterial consists in the fact that this work in three directions symmetrically, in comparison with PCF which work only in one direction.

3. CONCLUSIONS

In this communication we have estimated the influence of surfaces of two classes of metamaterials on the decontamination rate of liquid (or gases). An interesting effect appears in the dynamical regime of the contaminated fluids. In this case the transitions from laminar to turbulent flow may change drastically the decontamination rate. In the turbulent regime the Brown particles (viruses and bacteria) have a chaotic movement, so that time by time, they may achieve the evanescent zone of UV decontamination. This effect may be an advantage in the decontamination procedure. In other hand, increase the friction with decreasing the distances between the elements of meta-materials so the fluidity of liquid through such materials becomes difficult due to big adherence of liquid to the metamaterial surface.

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