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Light emitting fabric technologies for photodynamic therapy

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Abstract Photodynamic therapy (PDT) is considered to be a promising method for treating various types of cancer. A homogeneous and reproducible illumination during clinical PDT plays a determinant role in preventing under- or over-treatment. The development of flexible light sources would considerably improve the homogeneity of light delivery. The integration of optical fiber into flexible structures could offer an interesting alternative. This paper aims to describe different methods proposed to develop Side Emitting Optical Fibers (SEOF), and how these SEOF can be integrated in a flexible structure to improve light illumination of the skin during PDT. Four main techniques can be described: (i) light blanket integrating side-glowing optical fibers, (ii) light emitting panel composed of SEOF obtained by micro-perforations of the cladding, (iii) embroidery-based light emitting fabric, and (iv) woven-based light emitting fabric. Woven-based light emitting fabrics give the best performances: higher fluence rate, best homogeneity of light delivery, good flexibility.

Introduction

Photodynamic therapy (PDT) is considered to be a promising method for treating various types of cancer. A photosensitizer (or a precursor) is used to make the cells sensitive to light. Eventually, the tumor cells are exposed to the light leading the photosensitizer to interact with the oxygen in the cell. This photophysical mechanism produces toxic substances that destroy the tumor cell. Afterwards, the cell dies and is replaced by healthy tissue. A homogeneous and reproducible fluence delivery rate during clinical photodynamic therapy plays a determinant role in preventing under- or over-treatment. In dermatology, PDT is used to treat actinic keratoses (AKs). AKs are common pre-invasive

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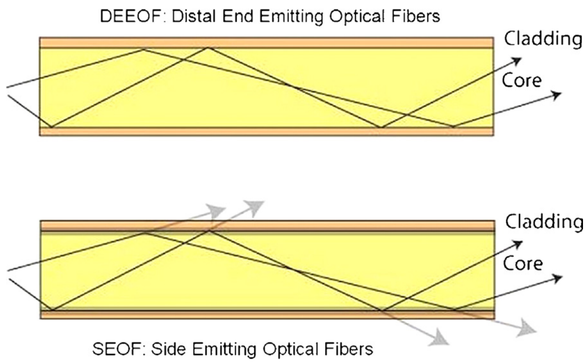

Fig. 1 Distal end emitting optical fibers vs Side-Emitting Optical Fibers.

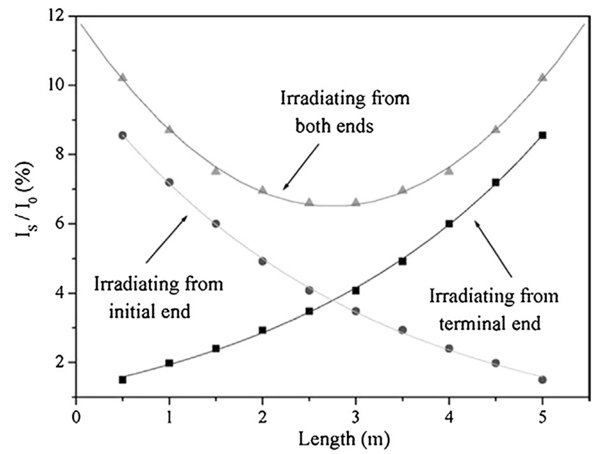

Fig. 2 Theoretical plot of light emission along a Side-Emitting Optical Fiber: (a) irradiating from initial end, (b) irradiating from terminal end, and (c) irradiating from both ends.

cancerous lesions in sun-exposed skin which negatively affect the quality of life in patients and may progress to invasive squamous cell carcinoma (SCC). AK usually develop on areas that are frequently exposed to the sun (e.g., face, ears, scalp, neck, forearms, and back of the hands). Studies have shown that if AK is untreated, AK may regress, or alternatively, may progress to SCC, with significant morbidity and possible lethal outcome. Predicting which AKs may progress to SCC is not possible, nor is the conversion rate for an AK to SCC clear: the transformation rate from an AK lesion to SCC within one year has been reported to be<1:1000. The malignant potential and the fact that it is impossible to predict which AK will evolve into SCC, have led to the common consensus that AKs have to be treated. Because of the high prevalence of AKs, their treatment represents a substantial workload, and must therefore be efficacious and easy to perform. Moreover, for patients an ideal treatment should be well tolerated and result in good cosmesis. The most commonly used treatments for AK are cryotherapy, topical chemotherapy and, more recently, photodynamic therapy (PDT) [1]. However, for this application, PDT is carried out with a wide variety of light sources delivering a broad range of more or less adapted light doses. Due to the complexities of the human anatomy, these light sources do not in fact deliver a uniform light distribution to the skin. For example, in the case of the LED system used usually in Dermatology, Moseley et al demonstrated that the irradiance may be as low as 38% of the central area at a lateral distance of only 2 cm [2].

Therefore, the development of flexible light sources would considerably improve the homogeneity of light delivery. The integration of optical fiber into flexible structures could offer an interesting alternative [3].

Optical fibers were originally developed to transmit the introduced light energy with minimum losses to their distal ends which emit like semi-point light sources. They are usually called: Distal End Emitting Optical Fibers under this condition, electromagnetic radiation is confined inside the core of the fiber and propagates along the fiber.

In Distal End Emitting Optical Fibers, total internal reflection of electromagnetic waves occurs at the boundary between core and cladding under the condition that the bend radius leads to light in the core falling below the critical angle. The confinement of light in an optical fiber is determined by the refractive indices of the fiber core ($n1$) and the surrounding cladding ($n2$). Total internal reflection occurs under the condition $n2 < n1$, and if the angle ψ between the normal to the interface core—cladding and the incident light ray is greater or equal to the critical angle $\psi c = \arcsin(n2/n1)$. If the bending radius of fibers exceeds the critical angle (ψc), a part of light can escape and produce a ''light spot''.

According to the literature, the intensity of side emitted light decreases with the distance x from the border of the fabric [4]. The light intensity as a function of the actual fiber length x can be expressed as:

$$I(x) = I_0 \exp(-kx) \qquad (1)$$

where, I stands for light intensity ($\mu W\,cm^{-2}$), I_0 is the input light intensity, and k is the side-scattering efficiency coefficient.

Recently, different methods were developed to promote light emission via the side surfaces of an optical fiber. The side-emission effect is created by ''leaking'' some light from the fiber's core to its cladding and further via the outer jacket to the surrounding medium. These optical fibers are so-called Side-Emitting Optical Fibers (SEOF). Fig. 1 illustrates the principle of a DEEOF and a SEOF.

In the case of SEOF the light leaks out from their surface. Side emission occurs if the light incidence angle is smaller than the critical angle. This effect can be obtained by the increasing of cladding refractive index or by decreasing of core refractive index. It is possible to use multiple micro-bending of core or cladding; using particulates causes reflection into core/cladding or creation of geometric asymmetry in the core/cladding system [5].

This paper aims to describe the different methods proposed to develop SEOF, and how these SEOF can be integrated in a flexible structure to improve light illumination of the skin during PDT. The characteristics of the different Light Emitting Fabrics are summarized in Table 1.