Investigation of light coupling techniques for electrospun polymer-optical nanofibers

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In this work an evanescent field coupling technique for selective light coupling in and out of electrospun polymer nanofibers is theoretically investigated. Investigations carried out by simulating nanofiber behaviour and coupling efficiency with the waveoptical RSoft software.

1 Introduction

Optical micro- and nanofibers (MNFs) enable to guide light on the micro and nanoscale [1]. Compared to regular optical fibers they thus offer several advantages such as tight optical confinement, strong evanescent fields and small fiber mass. Tight optical confinement allows optical wave-guiding with small bending radius without significant losses. For instance, radii of only several micrometers have been reported with bend losses of only 1-2 dB [2]. Furthermore, the strong evanescent fields enable enhanced near-field interaction between the wave-guide and the surroundings [3] which is advantageous with regard of sensing applications. Therefore, MNFs have been applied in the past for applications ranging from optical sensors to light emitting devices, for instance. However, a simple and cost-efficient fabrication method as well as an efficient light coupling technique for MNFs is still critical.

Electrospinning is a nanotechnology which allows the fabrication of polymer fibers on the micro- and nanometer scale. The process works with an electric field to accelerate a liquid polymer solution or melt. The resulting fibers elongate and reduce their diameter during the high speed phase and are placed on the grounded target device. Consequently, electrospinning enables a large-scale and cost-efficient fabrication of MNFs.

In this work a new approach to couple light selectively in and out of electrospun nanofibers is theoretically investigated. Based on evanescent coupling the light coupling between an angle-polished single-mode (SM) wave-guide and poly(methyl methacrylate) (PMMA) as well as poly(acrylonitrile) (PAN) nanofibers is explored. The angle-polished wave-guide could offer the advantage that it can be used to introduce light at arbitrary and spatially confined positions along the optical nanofiber structure which might, in future, be advantageous to study the light propagation through novel nanofiber structures.

2 Concept

Our approach to couple light selectively in and out of electrospun nanofibers is illustrated in Fig. 1. The light coupling wave-guide is polished with an angle in order to obtain total internal reflection at the wave-guide tip. The resulting evanescent field at the waveguide tip will interact with the MNF and light is being coupled into the fiber. The evanescent light coupling between both light wave-guides can be expressed theoretically as:

$$\phi_{crit} = arcsin(\frac{n_{SMF}}{n_{MNF}}) \quad (1)$$

where d, w and ϕ_{crit} are the diameter of the nanofiber, the gap width between the coupling wave-guide and the MNF as well as the angle between propagating light in the coupling wave-guide and the reflecting surface normal respectively.

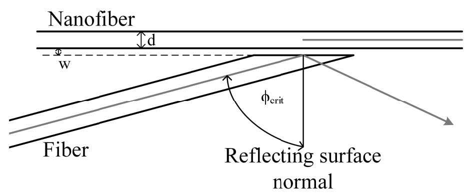

Fig. 1 *Schematics of the evanescent coupling method between fibers.*

3 Simulations

Evanescent light coupling is obtained when the propagation constants of the modes of the wave-guides being coupled are equal and the coupling coefficient and coupling length are greater than zero. According to Fig. 1 the propagation constants and coupling coefficients as well as the coupling length of the coupled modes can be tailored by optimizing the angle of the coupling wave-guide, the diameter of the MNF and the gap width. The proposed coupling approach shown in Fig. 1 has been simulated in 2D by using RSOFT and the finite-difference

DGaO Proceedings 2016 - http://www.dgao-proceedings.de - ISSN: 1614-8436 - urn:nbn:de:0287-2016-P051-0
submitted: 8.Jul.2016 - published: 12.Aug.2016

time-domain (FDTD) technique. In the simulation the coupling wave-guide is based on a standard optical fiber - Corning SMF28e. Using a refractive index profilometer the following parameters have been obtained for the coupling wave-guide: $n_{core} \approx 1.4694$ and $n_{clad} \approx 1.4605$ at $\lambda = 639$ nm wavelength; core diameter $d = 8.2$ µm. Furthermore, for the wave-guide core materials of the MNF PMMA and PAN have been applied for the simulations with refractive indices of $n_{PMMA} = 1.4886$ and $n_{PAN} = 1.5145$ at $\lambda = 639$ nm. First, the propagation constants of the fundamentals mode of PMMA and PAN based MNF have been calculated for different diameters. The results are illustrated in Fig. 2.

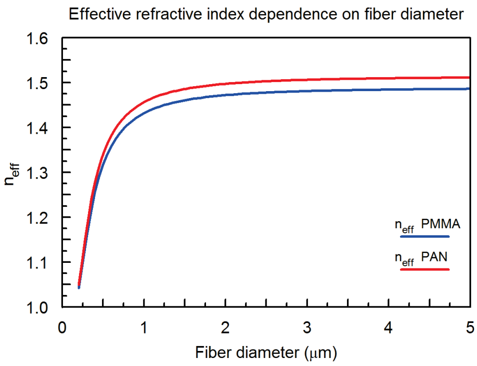

Fig. 2 *Effective refractive index (n_{eff}) dependence on diameter in PMMA (blue) and PAN (red) nanofibers.*

From Fig. 2 it follows that in order to evanescently couple light between the coupling wave-guide and the MNF the diameter of PMMA or PAN based MNF have to be less than approx. 1 µm, so that the resulting effective refractive index of the fundamental mode of the MNF is less than the refractive index of the coupling wave-guide core. Next the evanescent coupling to PMMA and PAN based MNFs has been simulated for different angles of the coupling wave-guide. The results are shown in Fig. 3.

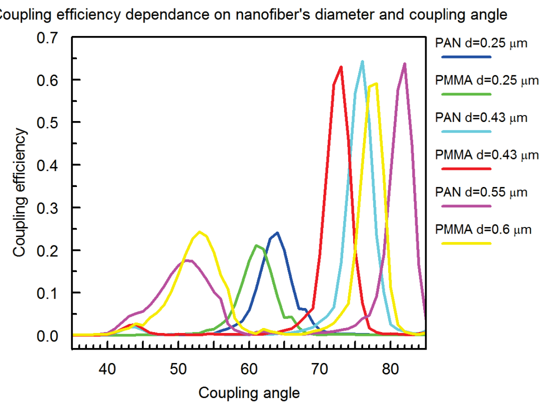

Fig. 3 *Dependence of coupling efficiency on coupling angle and MNF's diameter. Gap width is 10 µm.*

According to Fig. 3 the required coupling angle increases with an increasing MNF diameter due to an increasing effective refractive index of the fundamental mode of the MNF, which is consistent with Eq. 1. Moreover, the light coupling at small angles for MNF diameters above 0.5 µm is due to the excitation of higher order modes of the MNF. The maximum light intensity that is coupled between the coupling wave-guide and the MNF depends on the coupling coefficient and the coupling length. Since the coupling length is fixed by the angle and diameter of the coupling wave-guide the only parameter that can be tailored in order to obtain maximum light coupling at a given angle is the coupling coefficient and hence the gap w between both light wave-guides. In Fig. 3 the sensitivity of the coupling efficiency to the gap width w is illustrated.

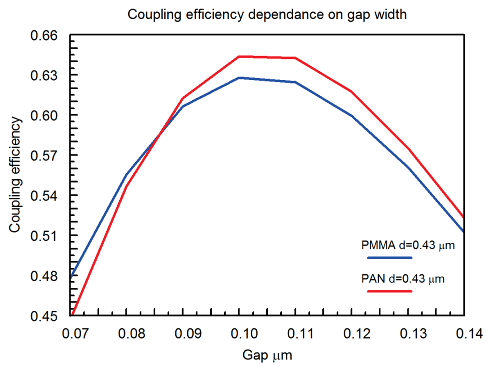

Fig. 4 *Coupling efficiency dependence on gap width between fibers. MNF's diameter is 0.43 µm, coupling angle is 73 deg.*

4 Conclusion

In this work a new approach to couple light selectively in and out of electrospun nanofibers has been theoretically investigated. Simulations verify that by using a polished coupling wave-guide light can be coupled evanescently to a MNF. Depending on the diameter of the MNF the required coupling angle can be determined. Furthermore, the coupling efficiency can be optimized by tailoring the gap width between both light wave-guides. Therefore, in future, the new coupling approach will be used to couple light in and out at arbitrary and spatially confined positions along electrospun nanofibers.

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