Resolving optical illumination distributions along an axially symmetric photodetecting fiber

by

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B.S. Ecole Polytechnique (2008)
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Submitted to the Department of Electrical Engineering and Computer Science in partial fulfillment of the requirements for the degree of

Master of Science in Electrical Engineering and Computer Science

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

February 2012

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Abstract

Photodetecting fibers of arbitrary length with internal metal, semiconductor and insulator domains have recently been demonstrated. These semiconductor devices display a continuous translational symmetry which presents challenges to the extraction of spatially resolved information. In this thesis, we overcome this seemingly fundamental limitation and achieve the detection and spatial localization of a single incident optical beam at sub-centimeter resolution, along a one-meter fiber section. Using an approach that breaks the axial symmetry through the constuction of a convex electrical potential along the fiber axis, we demonstrate the full reconstruction of an arbitrary rectangular optical wave profile. Finally, the localization of up to three points of illumination simultaneously incident on a photodetecting fiber is achieved.

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Acknowledgments

I would like to thank Dr. Fabien Sorin for initiating this project and for guiding me in every part of it, as well as Dr. Sylvain Danto for making the glass rods used in the fibers that I describe in this thesis.

I also thank Prof. Thierry Gacoin, leader of the Solid State Chemistry Group and director of the Chair Saint-Gobain at Ecole Polytechnique for putting me in touch with the Photonic Bandgap Fibers and Devices Group at MIT, and Saint-Gobain Research for the financial support that I have received during this project.

Finally, I want to thank Prof. Yoel Fink for his constant support and valuable advice in this project as in many others.

Contents

Introduction

Optical fibers rely on translational axial symmetry to enable long distance transmission. Their utility as a distributed sensing medium [1-3] relies on axial symmetry breaking either through the introduction of an apriori axial perturbation in the form of a bragg gratings [4], or through the use of optical time (or frequency) domain reflectometry techniques [5,6] which measure scattering from an adhoc axial inhomogeneity induced by the incident excitation. These have enabled the identification and localization of small fluctuations of various stimuli such as temperature [7-9] and stress [10-11] along the fiber axis. Due to the inert properties of the silica material, most excitations that could be detected were the ones that led to structural changes, importantly excluding the detection of radiation at optical frequencies. Recently, a variety of approaches have been employed, aimed at incorporating a broader range of materials into fibers. [12-20]. In particular, multimaterial fibers with metallic and semiconductor domains have presented the possibility of increasing the number of detectable excitations to photons and phonons [19-25], over unprecedented length and surface area. Several applications have been proposed for these fiber devices in imaging [23,24], industrial monitoring [26,27], remote sensing and functional fabrics [20,21].

So far however, the challenges associated with resolving the intensity distribution of optical excitations along the fiber axis have not been addressed. Here we propose an approach that allows extraction of axially resolved information in a fiber that is uniform along its length without necessitating fast electronics or complex detection architectures. We initially establish the axial detection principle by fabricating the simplest geometry that supports a convex potential profile designed to break the fiber's axial symmetry. We demonstrate that under conditions that we specify, that simplest geometry can be used for the localization of a single beam of light. Then, an optimal structure which involves a hybrid solid-core/thin-film cross-sectional design is introduced that allows to impose and vary convex electrical potential along a thin-film photodetecting fiber. We demonstrate the localization of a point of illumination along a one-meter photodetecting fiber axis with a sub-centimeter resolution. Moreover, we show how the width of the incoming beam and the generated photoconductivity can also be extracted. Finally, we demonstrate the spatial resolution of three simultaneously incident beams under given constraints.

1 Convex electrical potential along the fiber

1.1 Traditional fiber design

1.1.1 Principle of photodetection with fibers

Photodetecting fibers typically comprise a semiconducting chalcogenide glass contacted by metallic electrodes and surrounded by a polymer matrix [19-21]. These materials are assembled at the preform level and subsequently thermally drawn into uniform functional fibers of potentially hundreds of meters in length, as illustrated in Fig 1(A1). An electric potential $V(z)$ across the semiconductor can be imposed along the fiber length by applying a potential drop V_0 at one end as depicted in Fig 1(A2). As a result, a linear current density j_{dark} is generated in the semiconductor in the dark, between the electrodes. When an incoming optical wave front with an arbitrary photon flux distribution $\Phi_0(z)$ is incident on a fiber of total length L, the conductivity is locally changed and a photo-current (total current measured minus the dark current) is generated due to the photoconducting effect in semiconductors, as illustrated in Fig 1(A2). The measured photo-current in the external circuitry is the sum of the generated current density $j_{ph}(z)$ along the entire fiber length and has the general form:

$$i_{ph} = C \int_0^L V(z)\sigma_{ph}(z)dz \tag{1}$$

where C depends on the materials and geometry and is uniform along the fiber axis, and σ_{ph} is the locally generated film photo-conductivity that depends linearly on $\Phi_0(z)$ in the linear regime considered [22-24,30-32]. A more detailed calculation is carried further down this thesis. Note that we neglect the diffusion of generated free carriers along the fiber axis since it occurs over the order of a micrometer, several orders of magnitude lower than the expected resolution (millimeter range).

1.1.2 Limitations and proposed solution

For the photodetecting fibers considered so far, the conductivity of the semiconductor in the dark and under illumination has been orders of magnitude lower than the one of the metallic electrodes. These electrodes could hence be considered equipotential, and $V(z) = V_0$ along the fiber axis over extend lengths. As a result, j_{dark} is also uniform as depicted on the graph in Fig 1(A2). Moreover, the photo-current measured in the external circuitry integrates the photo-conductivity distribution $\sigma_{ph}(z)$ along the fiber length. This single, global current measurement does not contain any local information about the incident optical intensity distribution along the fiber axis. In particular, even the axial position of a single incoming optical beam could not be reconstructed. To alleviate this limitation, we propose an approach that breaks the axial symmetry of this fiber system and enables to impose various non-uniform electric potential distributions along the fiber axis. By doing so, we can generate and measure several global photo-currents i_{ph} where the fixed and unknown distribution $\sigma_{ph}(z)$ is modulated by different known voltage distributions $V(z)$. We will then be able to access several independent photo-

(A) Preform-to-Fiber approach

(A1) Thermal Drawing

Electrodes Conducting Polymer Insulator Semiconductor

(A2) Connected Fiber

(B) Fiber Cross Section

Metal

Glass

PSU

CPC

100 μm

(C) Fiber Equivalent Circuit

Figure 1: (A1): 3D Schematic of the multimaterial fiber thermal drawing fabrication approach. (A2): Schematic of a connected photodetecting fiber with an illumination event. The graph represents the linear current density in the dark and under the represented illumination. B: Scanning Electron Microscope micrograph of the fiber cross-section (inset: zoom-in on the contact between the core and the CPC electrode); C: Schematic of the fiber system's equivalent circuit.

current measurements from which information about the intensity distribution along the fiber axis will be extracted, as we will see.

1.2   Establishing a non-uniform electric potential

1.2.1   Conductive Polycarbonate

To controllably impose a non-uniform electrical potential profile $V(z)$, we propose to replace one (or both) metallic conducts by a composite material that has a higher electrical resistivity. This electrode, or resistive channel, can no longer be considered equipotential and the potential drop across the semiconductor will vary along the fiber axis. An ideal material for this resistive channel was found to be a composite polymer recently successfully drawn inside multimaterial fibers [27], that embeds Carbon

black nanoparticles inside a Polycarbonate matrix (hereafter: conducting polycarbonate or CPC) [28]. The CPC resistivity, ρ_{cpc} (1-10 $\Omega.m$ as measured post-drawing), lies in-between the low resistivity of metallic elements (typically 10^{-7} $\Omega.m$) and the high resistivity of chalcogenide glasses (typically $10^6 - 10^{12}$ $\Omega.m$) used in multimaterial fibers. It is very weakly dependant on the optical radiations considered so that it will not interfere with the detection process.

1.2.2 Convex potential

To validate this approach we first demonstrate the drawing compatibility of these materials. We fabricated a photodetecting fiber with a semiconducting chalcogenide glass core (of composition $As_{40}Se_{50}Te_{10}$) contacted by one metallic electrode ($Sn_{63}Pb_{37}$) and by another conduct made out of the proposed CPC composite. A Scanning Electron Microscope (SEM) micrograph of the resulting fiber cross-section is shown in Fig 1B that demonstrate the excellent cross-sectional features obtained. To first theoretically analyse this new system, we depict its equivalent circuit in Fig 1C. The semiconducting core can be modelled as multiple resistors in parallel, while the CPC channel is comprised of resistors in series. To find the voltage distribution $V(z)$ in this circuit, we can apply Kirchoff's laws at point A:

$$\frac{V(z) - V(z - dz)}{R_{cpc}} = \frac{V(z + dz) - V(z)}{R_{cpc}} - \frac{V(z)}{R_g} \text{ , or } \frac{\partial^2 V}{\partial z^2} = \frac{R_{cpc}}{R_g dz^2} V(z) \qquad (2)$$

or simply:

$$\frac{\partial^2 V}{\partial z^2} = \frac{V(z)}{\delta(z)^2} \qquad (3)$$

with:

$$\delta(z) = \sqrt{\frac{\rho_g(z)}{\rho_{cpc}} \frac{\pi}{2} S_{cpc}} \qquad (4)$$

where $R_{cpc} = \rho_{cpc} \dfrac{dz}{S_{cpc}}$ is the resistance of the CPC channel over an infinitesimal distance dz, S_{cpc} being the surface area of the CPC electrode in the fiber cross-section. Similarly, R_g is the resistance of a slab of cylindrical semiconducting core of length dz whose value depends on the glass geometry and is calculated for both a thin cylindrical film and a solid-core of glass in Appendix A. The new parameter δ has the dimensionality of a length and is referred to as the characteristic length of the fiber system. It can be tuned by engineering the glass composition (hence changing ρ_g), as well as the structure and geometry of the fiber.

Two sets of boundary conditions depicted in Fig 2 can be defined for this system: BC(1) where one fiber end ($z = 0$ or L) is brought to a potential $V^{BC(1)}(0) = V_0$ while the other ($z = L$ or 0) is left floating, locally resulting in $\dfrac{\partial V^{BC(1)}}{\partial z} = 0$ since no accumulation of charges is expected; and BC(2) where we apply a voltage at both fiber ends, $V^{BC(2)}(0) = V_0$ and $V^{BC(2)}(L) = V_L$. The two potential profiles can then be derived when δ is independent of z, and are given by two *convex* functions:

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$$V^{BC1}(z) = \frac{V_0 \cosh\left(\frac{L-z}{\delta}\right)}{\cosh\left(\frac{L}{\delta}\right)} \qquad (5)$$

$$V^{BC2}(z) = \frac{V_0 \sinh h\left(\frac{L-z}{\delta}\right) + V_L \sinh h\left(\frac{z}{\delta}\right)}{\sinh\left(\frac{L}{\delta}\right)} \qquad (6)$$

(A) Boundary condition 1 (BC1)

(B) Boundary condition 2 (BC2)

Figure 2: (A) Schematic of the fiber contact for boundary conditions (1) and graph representing the experimental results (dots) and the fitted theoretical model (lines) of the voltage profile between the CPC electrode and the metallic conduct at different points along the fiber axis, when the fiber is under BC(1) and for different fibers: in black, AST_{10} thin-film; in blue, AST_{10} core and in red, AST_{18}. (B) Same as (A) but when the fiber is under BC(2).

1.2.3 Experimental results

To assess our model, we fabricated three fibers with different materials and structures. All fibers have one metallic electrode ($Sn_{63}Pb_{37}$ alloy) and one CPC electrode of same size. Two fibers have a solid-core structure like the one shown in Fig 1B, with two different glass compositions from the chalcogenide system As-Se-Te, $As_{40}Se_{50}Te_{10}$ (referred to as AST_{10}) and $As_{40}Se_{42}Te_{18}$ (referred to as AST_{18}). The third fiber has a thin-film structure with a 500 nm layer of $As_{40}Se_{50}Te_{10}$ [22,24]. This thin film structure is expected to have a very large characteristic length since its conductance is many orders-of-magnitude lower than the one of both metallic and CPC electrodes. In solid-core fibers however, δ should be of the order of the fiber length, inducing a significant variation in the potential profile. Separate measurement of the CPC electrode resistivity ($\rho_{cpc} = 1.4\Omega.m$ and $\rho_{cpc} = 1.2\Omega.m$ in pieces from the AST_{10} and AST_{18} fibers respectively) and the glass conductivities lead to expected δ values of 40 cm and 9 cm in the AST_{10} and AST_{18} fibers respectively, the higher conductivity of AST_{18} being responsible for the lower δ parameter [33].

We then cut a 60-cm-long piece from each fiber and made several points of contact on the CPC electrodes while contacting the metallic conduct at a single location. We applied a 50 V potential difference for both BC(1) and BC(2), and measured the potential drop between the contact points along the CPC channel and the equipotential metallic conduct, using a Keithley 6517A multimeter. The experiment was performed in the dark to ensure the uniformity of δ. The results are presented in Fig 2 where the data points are the experimental measurements while the curves represent the theoretical model derived above, fitted over δ. As we expected, the thin-film fiber maintains a uniform potential along its axis. For solid-core fibers, the fitting values (43 cm and 11 cm for BC(1), and 44 cm and 11 cm for BC(2) for AST_{10} and AST_{18} fibers respectively) match very well with the expected δ parameters given above. The discrepancy is due to errors in measuring the different dimensions in the fiber, and potential slight non-uniformity of the glass conductivity due to local parasitic crystallization during the fabrication process [34]. Noticeably, the δ values obtained for both boundary conditions are in excellent agreement, which strongly validates our model.

2 Simple device: solid-core or thin-film structure

We present here the first device that we have designed in this project. Using either the solid core or thin-film fiber structure presented in the previous section with the boundary conditions set BC(1) we demonstrate how under specific conditions one can locate a single beam of light.

We consider an uniform beam of light along the x axis localised at $x = x_0$, with a width of Δx (Fig 3). The beam is entirely contained between $x = 0$ and $x = L$ (i.e $\frac{\Delta x}{2} < x_0 < L - \frac{\Delta x}{2}$ and $\Delta x < \frac{L}{2}$). The intensity of the beam is independent of the angle θ in cylindrical coordinates. The flux of photon $\Phi(x)$ (per unit of surface) at the surface of the glass is then given by:

$$\Phi(x) = \Phi_0 \quad if\,|x - x_0| < \frac{\Delta x}{2}$$
$$= 0 \qquad otherwise$$

(7)

Figure 3: Profile of the photon beam to be detected

2.1 Presentation of the device

In this device, a photodetecting fiber as described previously is connected to a tension generator at one end, and is free at the other. The device is shown on the Fig 4 (where the diameter is exaggerated). The tension V_0 can be applied at $x = 0$ or at $x = L$, resulting in a measured current i_0 or i_L given by the amperemeter. These two currents are expected to depend on the properties of the beam ($x_0, \Delta x, \Phi_0$), and we will show how the ratio of them leads to the position x_0 of the beam.

Therefore, we need to establish the expressions of $i_0(x_0, \Delta x, \Phi_0)$ and $i_L(x_0, \Delta x, \Phi_0)$. But before doing so, we will first study the expected behavior of the device under homogeneous light (in the dark, for instance), and compare the experimental results to the theory.

In the following, we always give the analytical expressions for physical quantities - such as the current flowing in the device - for the solid-core as well as for the thin-film geometries. Thin-film fibers are, as will be shown, expected to display a better

Figure 4: The photodetecting device, allowing the user to measure either i_0 or i_L.

detectivity, but we have seen in the previous section that the length δ associated with this structure is much longer than in solid-core fibers and therefore, for practical reasons (working with devices shorter than one meter) all experiments have been carried on the solid-core structure.

2.2 Behavior under homogeneous light

2.2.1 Potential

Under homogeneous light, the resistivity of the glass is uniform in the fiber. Thus, δ does not depend on x and as mentioned above, the voltages in the fiber, $V_0(x)$ and $V_L(x)$ (respectively if V_0 is applied at x=0 or x=L) are given by:

$$V_0(x) = V_0 \frac{\cosh \dfrac{L-x}{\delta}}{\cosh \dfrac{L}{\delta}} \tag{8a}$$

$$V_L(x) = V_0 \frac{\cosh \dfrac{x}{\delta}}{\cosh \dfrac{L}{\delta}} \tag{8b}$$

2.2.2 Dark current

The glass is an insulator, but as its resistivity is finite it allows a certain current to flow between the electrodes, under homogeneous light. We call this current 'dark current' because of its role in the detection of the single beam (see section 2.4) This dark current can easily be calculated, by using the expressions (53) and (57) found for the resistance of a glass core or of a glass layer in 3.3.2. Indeed, in both cases, it is given by:

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$$i_d = \int_0^L \frac{V(x)}{R_g} \tag{9}$$

Depending on the geometry, the dark current is thus given by:

$$i_d^{core} = \frac{2\delta V_0}{\rho_g \pi} \tanh \frac{L}{\delta} \tag{10a}$$

$$i_d^{layer} = \frac{2\delta V_0 t_g}{\rho_g \pi r_g} \tanh \frac{L}{\delta} \tag{10b}$$

We see with these equations that the dark current is much higher in the glass core than it is in a thin glass layer of the same radius.

2.2.3 Experimental results

The equations (10) show a simple behavior of the dark current with the length of the fiber: an hyperbolic tangent. This trend can be verified by measuring the dark current flowing in one device, while cutting bits of the fiber from its free end (Fig 5). This actually gives us another way of determining the value of δ by simply fitting the curve $I_0 \tanh \frac{L}{\delta}$ to the data. We did so for two different samples of fiber using AST_{10} and AST_{18} solid-cores The results are shown in Fig 6.

Figure 5: The cutback measurement.

For the AST_{18} sample, the correlation was $R^2 = 0.9945$ and led to $\delta = 15cm$. For the AST_{10} sample, the correlation was $R^2 > 0.9999$ and led to $\delta = 40cm$. Besides, as we can see in (10), we can deduce from the value of I_0 the value of the resistivity of both glasses. With this method, we found $\rho_{18} = 8,1x10^6 \ \Omega.m$ and $\rho_{10} = 7,7x10^7 \ \Omega.m$.

It is important to compare these results to those that a fiber with two metallic electrodes would have. In such a fiber, the current would be proportional to the length of the fiber. We would thus observe a straight line on the Fig 6. Besides, these excellent correlations show that the calculated profile of $V(x)$ is very close to the real profile. This means that the equations and conditions at the boundaries are the right ones, and also

Current measured in the dark Vs Length of the fiber

Data and fitted hyperbolic tangent

Figure 6: The cutback measurement.

that our fibers do not present major defects, and that their diameter is uniform along the length.

2.3 Behavior under the beam of light

If a beam of light reaches the fiber, photons will be absorbed by the glass between $x_0^- = x_0 - \frac{\Delta x}{2}$ and $x_0^+ = x_0 + \frac{\Delta x}{2}$, creating charge carriers. As the conductivity of the glass is proportionnal to the density of charge carriers, it will locally increase. The profile $V(x)$ will thus not be the same as under homogeneous light, and will depend on the features of the beam.

Before calculating the new profile $V(x)$ we first determine the density of charge carriers photogenerated under the beam of light

2.3.1 Density of carriers

In this project, we have limited our study to distributions of light constant in time. Thus, we have always neglected the time to establish the potential $V(x)$, as well as the time for the device to reach a steady state under illumination. This means that the measurements of i_0 and i_L must be made when the current is stable, which can sometimes take a few minutes.

Along the r direction, the beam is absorbed by the glass with a coefficient of absorption α_g, resulting in a photon flux $\Phi_{core}(r, x)$ or $\Phi_{layer}(r, x)$ (depending on the geometry) inside the glass, given by:

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$$\Phi_{core}(r,x) = \Phi_0 e^{-\alpha_g(r_g-r)} \qquad\qquad if \ \ x \in [x_0^-\,;x_0^+] \ \text{and} \ r < r_g \qquad (11a)$$

$$\Phi_{layer}(r,x) = \Phi_0 e^{-\alpha_g(r_g+t_g-r)} \qquad if \ \ x \in [x_0^-\,;x_0^+] \ \text{and} \ r_g < r < r_g + t_g \qquad (11b)$$

$$= 0 \qquad\qquad\qquad\qquad\qquad \text{otherwise} \qquad (11c)$$

In those expressions, we neglected the shadow caused be the electrodes, as well as the absorption by the cladding of the fiber, that in fact slightly modify Φ_0. It thus appears that as $\frac{1}{\alpha_g}$ is usually much smaller than r_g, the glass core behaves as a glass layer whose thickness is a few $\frac{1}{\alpha_g}$. From now we will carry on with the glass core geometry, r will always be smaller than r_g, meaning that we study the behavior of the core of the fiber. The calculations for the glass layer geometry as well as the final results are similar to those of the glass core geometry.

As each photon absorbed by the glass creates an electron-hole pair, the rate $G(r,x)$ of generation of charge carriers in the glass is given by the variation of the photon flux as it goes deeper in the glass:

$$G(r,x) = \frac{\partial \Phi(r,x)}{\partial r} = \alpha_g \Phi_0 e^{-\alpha_g(r_g-r)} \ \ \text{if} \ |x - x_0| < \frac{\Delta x}{2}$$
$$= 0 \qquad\qquad otherwise \qquad (12)$$

In the glass, the volumic density of electrons (holes) is n (p), and the volumic density of surplus of electrons (holes) is Δn (Δp). Those quantities evolve with time as following:

$$\frac{\partial n}{\partial t} = \frac{\partial \Phi}{\partial z} - \frac{\Delta n}{\tau} + \frac{1}{e}\frac{\partial J_n}{\partial r} \qquad (13a)$$

$$\frac{\partial p}{\partial t} = \frac{\partial \Phi}{\partial z} - \frac{\Delta p}{\tau} - \frac{1}{e}\frac{\partial J_p}{\partial r} \qquad (13b)$$

where τ is the recombination time of the carriers (which has to be the same for the electrons and the holes). J_n (J_p) is the density of current for the electrons (for the holes). This density is given by:

$$\frac{J_n}{e} = D_n\frac{\partial n}{\partial r} + n\,\mu_n\,E \qquad (14a)$$

$$\frac{J_p}{e} = -D_p\frac{\partial p}{\partial r} + n\,\mu_p\,E \qquad (14b)$$

where μ and D are the mobilities and the scattering coefficients of the carriers.

The glasses we are working with are usually p-type. This way the neutrality of the material is ensured by the holes (main charge carriers) and the initial number of electrons is always very small (thus $n + \Delta n \approx \Delta n$). After the time t_{eq}, a steady state is reached (because α_g varies with Φ_0 with a saturation mechanism). The equation for the electrons is therefore the following:

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$$\frac{\Delta n}{\tau} - D_n \frac{\partial^2}{\partial r^2} \Delta n - \frac{\partial}{\partial r}(n \, \mu_n \, E) = \alpha_g \Phi_0 e^{-\alpha_g(r_g - r)} \tag{15}$$

In absence of illumination, Δn is null. In those conditions, $\frac{\partial}{\partial r}(n \, \mu_n \, E) = 0$, and so, by neglecting $\Delta n \, \mu_n \, E$, the final equation for Δn, volumic density of the photogenerated electrons is, for $x \in [x_0^-; x_0^+]$

$$\frac{\Delta n}{\tau} - D_n \frac{\partial^2}{\partial r^2} \Delta n = \alpha_g \Phi_0 e^{-\alpha_g(r_g - r)} \tag{16}$$

The expression of Δn is thus of the following type, where A and B are to be determined:

$$\Delta n = A e^{\frac{r_g - r}{L_s}} + B e^{-\frac{r_g - r}{L_s}} + \frac{\alpha_g \tau \Phi_0}{1 - (\alpha_g L_s)^2} e^{-\alpha_g(r_g - r)} \tag{17}$$

where L_s is the scattering distance of the electrons in the glass $L_s = \sqrt{D_n \tau}$.

In order to determine A and B we have to write the conditions at the boundaries. In our case, the first condition is that no electron created by the light can get out of the glass at $r = r_g$. As the fiber polymer is an insulator this hypothesis is reasonable. The second condition is that, because of the symmetry, the current is null at the center of the glass core. Those two conditions mean that $J_n = D_n \frac{\partial n}{\partial r} = 0$ at $r = 0$ and $r = r_g$, which gives:

$$A - B = \frac{\alpha_g^2 L_s \tau \Phi_0}{1 - (\alpha_g L_s)^2} e^{-\alpha_g r_g} \tag{18a}$$

$$A e^{-\frac{r_g}{L_s}} - B e^{\frac{r_g}{L_s}} = \frac{\alpha_g^2 L_s \tau \Phi_0}{1 - (\alpha_g L_s)^2} \tag{18b}$$

Thus, the exact expression of $\Delta n(r, x)$, and of $n(x)$, number of photogenerated electrons in the fiber between x and $x + dx$ can be established. However, these expressions are uselessly complicated, and it should only be underlined that $\Delta n(r, x)$ and $n(x)$ are proportional to $\tau \Phi_0$ between x_0^- and x_0^+ and null outside this domain.

2.3.2   Potential

We can now describe the impact that the beam of light has on the profile of the potential $V(x)$ along the fiber, when a voltage V_0 is applied at one of its ends. Indeed, as charge carriers are created in the glass under illumination, its resistivity is bound to decrease. If a significant number of charge carriers are created, then the drop of resistivity between x_0^- and x_0^+ short-cuts the part of the fiber where $x > x_0^+$.

Let ρ_g' be the resistivity of the glass under illumination, where ρ_g is its resistivity in the dark (or under the homogeneous bagkground light). As the conductivity of the glass

follows the law $\sigma_g = \frac{1}{\rho_g} = Ne\mu_n$ where N is the total density of free charge carriers in the glass, then the relation between ρ_g and ρ'_g is simply:

$$\frac{1}{\rho'_g} = N'e\mu_n = Ne\mu_n + \Delta ne\mu_n = \frac{1}{\rho_g} + \Delta ne\mu_n \tag{19}$$

where Δn has been calculated in the section 2.3.1.

We define as well $\delta' = \delta\sqrt{\frac{\rho'_g}{\rho_g}}$, which is the characteristical distance of the drop of potential between x_0^- and x_0^+. The potential $V(x)$ across the glass and along the length of the fiber is now solution of the problem:

$$V(x) = \delta'^2 \frac{\partial^2 V}{\partial x^2} \qquad \text{if } x \in [x_0^-; x_0^+] \tag{20a}$$

$$V(x) = \delta^2 \frac{\partial^2 V}{\partial x^2} \qquad \text{otherwise} \tag{20b}$$

If we call $V^- = V(x_0^-)$ and $V^+ = V(x_0^+)$, two voltages that are for now unknown, then $V(x)$ is given by:

$$V(x) = V_1(x) = \frac{V^- \sinh\left(\frac{x}{\delta}\right) + V_0 \sinh\left(\frac{x_0^- - x}{\delta}\right)}{\sinh\left(\frac{x_0^-}{\delta}\right)} \qquad \text{if } x \in [0; x_0^-] \tag{21a}$$

$$V(x) = V_2(x) = \frac{V^+ \sinh\left(\frac{x - x_0^-}{\delta'}\right) + V^- \sinh\left(\frac{x_0^+ - x}{\delta'}\right)}{\sinh\left(\frac{\Delta x}{\delta'}\right)} \qquad \text{if } x \in [x_0^-; x_0^+] \tag{21b}$$

$$V(x) = V_3(x) = V^+ \frac{\cosh\left(\frac{L - x}{\delta'}\right)}{\cosh\left(\frac{L - x_0^+}{\delta'}\right)} \qquad \text{if } x \in [x_0^+; L] \tag{21c}$$

$$\tag{21d}$$

In order to determine V^- and V^+ we write that the electric field has to be continuous at $x = x_0^-$ and $x = x_0^+$, i.e.:

$$\frac{\partial V_1}{\partial x} = \frac{\partial V_2}{\partial x} \qquad \text{at } x_0^- \tag{22a}$$

$$\frac{\partial V_2}{\partial x} = \frac{\partial V_3}{\partial x} \qquad \text{at } x_0^+ \tag{22b}$$

$$\tag{22c}$$

Finally this lead to a 2x2 system for V^- and V^+:

$$V^- \left(\frac{1}{\delta \tanh \frac{x_0^-}{\delta}} + \frac{1}{\delta' \tanh \frac{\Delta x}{\delta'}} \right) \quad -V^+ \frac{1}{\delta' \sinh \frac{\Delta x}{\delta'}} \qquad\qquad = \frac{V_0}{\delta \sinh \frac{x_0^-}{\delta}}$$
$$\tag{23a}$$

$$-V^- \frac{1}{\delta' \sinh \frac{\Delta x}{\delta'}} \qquad\qquad +V^+ \left(\frac{1}{\delta' \tanh \frac{\Delta x}{\delta'}} + \frac{1}{\delta} \tanh \frac{L - x_0^-}{\delta} \right) = 0 \qquad \tag{23b}$$

It is easy to verify that this system has only one solution, that is:

$$V^- = V_0 \frac{\dfrac{\delta}{\delta' \tanh \frac{\Delta x}{\delta'}} + \tanh \frac{L - x_0^-}{\delta}}{\sinh \frac{x_0^-}{\delta} \left(\dfrac{\delta^2}{\delta'^2} + \dfrac{1}{\tanh \frac{x_0^-}{\delta}} \left(\dfrac{\delta}{\delta' \tanh \frac{\Delta x}{\delta'}} + \tanh \frac{L - x_0^-}{\delta} \right) + \dfrac{\delta \tanh \frac{L - x_0^-}{\delta}}{\delta' \tanh \frac{\Delta x}{\delta'}} \right)} \tag{24a}$$

$$V^+ = V_0 \frac{1}{\sinh \frac{x_0^-}{\delta} \sinh \frac{\Delta x}{\delta'} \left(\dfrac{\delta}{\delta'} + \dfrac{1}{\tanh \frac{x_0^-}{\delta}} \left(\dfrac{1}{\tanh \frac{\Delta x}{\delta'}} + \dfrac{\delta'}{\delta} \tanh \frac{L - x_0^-}{\delta} \right) + \dfrac{\tanh \frac{L - x_0^-}{\delta}}{\tanh \frac{\Delta x}{\delta'}} \right)} \tag{24b}$$

The profile of the potential can thus be deeply changed by a beam of light, if the power or the width of the beam is important enough. The Fig 7 shows, for a 5mm-wide beam at a position $x_0 = 10.25$cm of a 20.5cm-long fiber, how the profile of $V(x)$ is modified depending on the resistivity of the glass under illumination.

Profile of the voltage along a fiber for light dependent glass conductivity

Comsol simulation - beam of light between 10 and 10.5cm - System CPC - CPC

Figure 7: Profiles of the voltage for different alleged impacts of the light on the resistivity of the fiber between x=10cm and x=10.5cm

For a same width of the beam as well as a same resistivity ρ'_g under illumination, the profile of $V(x)$ can significatively vary with x_0, as shown in Fig 8. The beam of light bend the profile of the tension. The closer the beam is from the connected end of the fiber, the deeper is this effect. It is thus clear that the measured current depend on the position x_0 of the beam, and we will now calculate this current.

Figure 8: Profiles of the voltage for different positions of the 5mm-wide beam when $\rho'_g = \frac{\rho_g}{50}$

2.3.3 Current

Now that the profile of $V(x)$ is known, there are two ways of calculating the total current flowing from one electrode to the other through the glass, that are equivalent. A first approach is simply to integrate the current di flowing through the piece of glass between x and $x + dx$. As R_g is the resistance of such a piece of glass given in (53), we have, for a glass core geometry, the following expression for the total current:

$$I_1^{total} = \int_0^L \frac{2V(x)}{\rho_g(x)\pi}dx = \int_0^{x_0^-} \frac{2V_1(x)}{\rho_g\pi}dx + \int_{x_0^-}^{x_0^+} \frac{2V_2(x)}{\rho'_g\pi}dx + \int_{x_0^+}^L \frac{2V_3(x)}{\rho_g\pi}dx \quad (25)$$

where V_1, V_2 and V_3 are given in (21).

A second approach is to consider that the current divides itself in two different currents: a 'dark current' I_2^d, resulting from the integration of $V(x)$ given in (21) over the whole fiber of uniform resistivity ρ_g, and a photocurrent I_2^{ph}, resulting from the movement of the charge carriers photogenerated under the beam, a movement that is due to the voltage V_2 in that area. We will see in the section 2.4 why this approach is in practice very useful. With this approach, the 'dark current' I_2^d is given by:

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$$I_2^d = \int_0^L \frac{2V(x)}{\rho_g \pi} dx \tag{26}$$

In this case, the potential $V(x)$ across the glass and along the fiber is given by the equation (21). The electrons photogenerated move in the electric field $\mathbf{E}(r, \theta, x) = -\nabla V(r, \theta, x)$, with $V(r_g, 0, x) - V(r_g, \pi, x) = V(x)$. This electric field will therefore have the following shape:

$$\mathbf{E}(r, \theta, x) = -\frac{V(x)}{r_g} \mathbf{f}_\perp(r, \theta) - \frac{\partial V}{\partial x} \mathbf{e}_x \tag{27}$$

where $\mathbf{f}_\perp(r, \theta)$ is an adimensional vector field defined in the cross section $(\mathbf{e}_r, \mathbf{e}_\theta)$ of the glass. The variations of the potential along the $\mathbf{e}_x$ direction have a magnitude of the order of $\frac{V_0}{\delta'}$ where those in the cross section have a magnitude of the order of $\frac{V_0}{r_g}$. As δ in the final device will be around 50cm where r_g should never be more than 0.5mm, we can neglect the effect of the electric field along the direction $\mathbf{e}_x$ of the fiber, inside the glass.

The density of photocurrent will thus also be perpendicular to the axis of the fiber, and its exact expression is:

$$\mathbf{J}_{ph}(r, \theta, x) = -\Delta n(r, x) \, e \, \mu_n \, \mathbf{E}(r, \theta, x) \tag{28}$$

where $\Delta n(r, x)$, the volumic density of electrons photogenerated, has been calculated in the section 2.3.1. We will not give the explicit expression for $\mathbf{J}_{ph}(r, \theta, x)$ because it requires a complicated calculation, that is not needed. Indeed, we already know, thanks to the equations (17), (27) and (28), that the photocurrent per unit of length j^{ph} flowing through the fiber has the shape:

$$j^{ph}(x) = K\tau\mu_n e^{\frac{\Phi_0 V_2(x)}{l_g}} \quad \text{if} \ \ x \in [x_0^-; x_0^+] \tag{29}$$
$$= 0 \qquad\qquad\qquad \text{otherwise}$$

where K is a number and l_g a length depending of the geometry and of the properties of the glass. l_g depends on α_g, r_g, L_s and t_g in the case of the glass layer geometry. Again, a complicated integration would lead to the exact expression of K and l_g, but in the real device, several parameters have unknown values, and that it is the calibration of the device that allows us to determine the value of complicated objects like $K\tau\mu_n e^{\frac{\Phi_0 V_0}{l_g}}$, which is the only value we actually need.

Finally, the photocurrent I_2^{ph}, measured when a beam of width Δx, reaches the fiber at the position x_0 with a power of Φ_0 photons.$m^{-2}.s^{-1}$ when a voltage V_0 is applied at the position $x = 0$ is:

$$I_2^{ph} = \int_0^L j^{ph}(x)dx = \int_{x_0^-}^{x_0^+} K\tau\mu_n e^{\frac{\Phi_0 V_2(x)}{l_g}} dx \tag{30}$$

As the conductivity of the glass follows the law (19), the first method leads to another expression of I_1^{total}:

$$I_1^{total} = \int_0^{x_0^-} \frac{2V_1(x)}{\rho_g \pi} dx + \int_{x_0^-}^{x_0^+} \frac{2V_2(x)}{\rho_g' \pi} dx + \int_{x_0^+}^{L} \frac{2V_3(x)}{\rho_g \pi} dx \tag{31a}$$

$$I_1^{total} = \int_0^{L} \frac{2V(x)}{\rho_g \pi} dx + \int_{x_0^-}^{x_0^+} \mu_n e \int_{S_g} \Delta n \frac{\mathbf{f}_\perp(r,\theta)}{r_g} r dr d\theta \frac{2V_2(x)}{\pi} dx \tag{31b}$$

where we recognize the sum of I_2^d and I_2^{ph} when integrating Δn on the cross section of the glass. The two approaches and thus equivalent. We thus have the choice to carry on using the unknown parameters $\frac{K\tau\mu_n e}{l_g}$ or simply δ'. Indeed, we have just shown that δ' contains ρ_g' that is directly linked to the absorption mechanism whose parameter is $\frac{K\tau\mu_n e}{l_g}$). We choose to carry on using the parameter δ' that simplifies the following expression of the current. Indeed, we can integrate (25) to obtain an explicit expression for the total current:

$$I^{total} = \frac{2\delta V_0}{\pi \rho_g} \left(-\frac{V^-}{V_0 \sinh \frac{x_0^-}{\delta}} + \tanh \frac{x_0^-}{\delta} \right) \tag{32}$$

where we used (23), and where V^- is given in (24).

2.3.4 Experimental results

In the previous section, we obtained the expression (32) of the total current flowing in the device when exposed to a beam of light and when a voltage V_0 is applied at the end $x = 0$ of the fiber. In the real system, because the temperature as well as the stress endured by the fiber during the process of drawing can induce variations of the resistivities ρ_g and ρ_{cpc}, δ is badly known. These variations will be discussed in the section 3.3.2. Of course, as it depends on the features of the beam, δ' is totally unknown as well.

In order to determine these parameters, as well as to verify that the found expression for the current is right, we set up a simple experiment: a single beam of light of known position and width enlightens the device that delivers a tension V_0 either at $x = 0$ or at $x = L$. We measured the current (i_0 or i_L) for several position x_0 of the light and used Matlab to fit to the experimental data one of the following expressions (obtained by combining (24) and (32) for the expression of $i_0(x_0)$, and doing a similar calculation for $i_L(x_0)$):

$$i_0(x_0) = \frac{2\delta V_0}{\pi \rho_g} \left(-\frac{\frac{\delta}{\delta' \tanh \frac{\Delta x}{\delta'}} + \tanh \frac{L-x_0^-}{\delta}}{\sinh^2 \frac{x_0^-}{\delta} \left(\frac{\delta^2}{\delta'^2} + \frac{1}{\tanh \frac{x_0^-}{\delta}} \left(\frac{\delta}{\delta' \tanh \frac{\Delta x}{\delta'}} + \tanh \frac{L-x_0^-}{\delta} \right) + \frac{\delta \tanh \frac{L-x_0^-}{\delta}}{\delta' \tanh \frac{\Delta x}{\delta'}} \right)} + \tanh \frac{x_0^-}{\delta} \right) \tag{33a}$$

$$i_L(x_0) = \frac{2\delta V_0}{\pi \rho_g} \left(-\frac{\frac{\delta}{\delta' \tanh \frac{\Delta x}{\delta'}} + \tanh \frac{x_0^+}{\delta}}{\sinh^2 \frac{L-x_0^+}{\delta} \left(\frac{\delta^2}{\delta'^2} + \frac{1}{\tanh \frac{L-x_0^+}{\delta}} \left(\frac{\delta}{\delta' \tanh \frac{\Delta x}{\delta'}} + \tanh \frac{x_0^+}{\delta} \right) + \frac{\delta \tanh \frac{x_0^+}{\delta}}{\delta' \tanh \frac{\Delta x}{\delta'}} \right)} + \tanh \frac{L-x_0^+}{\delta} \right) \tag{33b}$$

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where δ, δ' and ρ_g were the parameters to be determined. We summarize here the results obtained for several samples of two glass-core fibers (AST_{10} and AST_{18}) (the goodness of fit R^2 is also given) and a few examples are given in Fig 9. In several case, two different values for these parameters have been found for the same sample, one at the $x = 0$ end and another at the $x = L$ end. This is due to the fact that the diameter of the fiber is not always exactly constant along the length.

Figure 9: For different samples, fitted expression (33) to the experimental data.

Glass	Sample	End	Electrodes	δ (cm)	δ' (cm)	ρ_g (MOhm.m)	R^2
AST18	IV	$x = 0$	CPC-CPC	12.62	3.83	4.24	0.9984
AST18	VII	$x = 0$	CPC-CPC	20.73	6.44	5.32	0.9956
AST18	VII	$x = L$	CPC-CPC	21.69	6.18	5.28	0.9939
AST18	VIII	$x = 0$	CPC-metal	9.06	2.67	3.19	0.9993
AST18	VIII	$x = L$	CPC-metal	10.22	2.45	3.89	0.9958
AST18	IX	$x = 0$	CPC-CPC	16.29	3.38	5.66	0.9995
AST18	IX	$x = L$	CPC-CPC	12.16	2.59	3.93	0.9978
AST10	5	$x = 0$	CPC-CPC	37.35	6.93	48.7	0.9975
AST10	9	$x = 0$	CPC-CPC	35.02	6.23	60.5	0.9984
AST10	14	$x = 0$	CPC-metal	28.74	4.83	57.5	0.9966
AST10	21	$x = 0$	CPC-metal	34.24	5.64	65.5	0.9971

As for the found values of δ', they depend a lot on the width Δx of the beam entered by the user in the Matlab program. Yet, this width is badly known because scattering

of the light occurs in the cladding of the fiber, leading to a beam of light seen by the glass whose shape is expected to be quite different from the one described in Fig 3. In this case, Δx has been estimated at 5 mm. But we could re-fit the expressions (33) to the data with a different value of Δx, it would change the values found for δ'. This is because Δx and δ' are linked by a relation that gives the total quantity of light absorbed by the fiber. The values of δ' are thus only approximations, that are useful to estimate the impact of the light on the resistivity of the glass. Here we can see that δ' is usually 3 to 6 times shorter than δ, meaning that the resistivity of the glass drops by ten to thirty times under the light that has been used in this experiment. However, the values found for δ and ρ_g are independent of this estimation of Δx, and we can use them to verify (Fig 10) that δ is really proportionnal to the diameter of the fiber, as predicted in (55).

Delta in the dark Vs Diameter of the fiber
Draw June AST18 and July AST10

Figure 10: For a given glass, the proportionnality between δ and the diameter is observed.

2.4 Simplification of the profile expression

The previous results (Fig 9) show that the expressions (33) of $i_0^{ph}(x_0)$ and $i_L^{ph}(x_0)$ are accurate. Yet, the complexity of these expressions does not allow the user to retrieve the position x_0 of the beam from the values of the currents.

However, it has been witnessed, and verified with Matlab, that for reasonably wide ($\Delta x < 10mm$) and powerful (ρ_g divided by less than 100) beams, the shape of the function $V(x_0)$ is fairly similar to the profile (8) of the tension $V(x)$ under homogeneous illumination, with a new couple (δ^{eff}, V_0^{eff}):

$$V_0(x_0) = V_0^{eff} \frac{\cosh \dfrac{L - x_0}{\delta^{eff}}}{\cosh \dfrac{L}{\delta^{eff}}} \qquad\qquad contact\ at\ x = 0 \qquad (34a)$$

$$V_L(x_0) = V_0^{eff} \frac{\cosh \dfrac{x_0}{\delta^{eff}}}{\cosh \dfrac{L}{\delta^{eff}}} \qquad\qquad contact\ at\ x = L \qquad (34b)$$

The following array shows, for different sets $(L, \Delta x, \frac{\rho_g}{\rho_g'})$ (with $V_0 = 100V$), how good, and for which values of $(\delta^{eff}, V_0^{eff})$ this simplified expression fits the exact expression of $V(x_0)$ that is:

$$V(x_0) = \frac{V^+ \sinh\left(\dfrac{\Delta x}{2\delta'}\right) + V^- \sinh\left(\dfrac{\Delta x}{2\delta'}\right)}{\sinh\left(\dfrac{\Delta x}{\delta'}\right)} \qquad (35)$$

L (cm)	δ (cm)	Δx (mm)	$\dfrac{\rho_g}{\rho_g'}$	$\dfrac{\delta}{\delta^{eff}}$	V_0^{eff} (V)	R^2
41	20	5	20	1.15	95.55	0.9986
41	20	5	50	1.32	89.08	0.9932
41	20	5	75	1.45	84.53	0.9873
41	20	5	100	1.56	81.65	0.9810
20.5	10	10	20	1.43	78.70	0.9891
20.5	10	10	50	1.86	58.86	0.9658
20.5	10	10	75	2.16	48.83	0.9526
20.5	10	10	100	2.44	41.73	0.9427
20.5	10	2	100	1.47	84.07	0.9858
100	10	5	75	1.59	64.94	0.9862
100	20	5	75	1.38	81.68	0.9900
100	150	5	75	1.28	100.8	0.9949
100	300	5	75	1.30	100.4	0.9908

We thus see that, for the typical set of values with which we are working - where Δx is much smaller than δ who is itself a few times smaller than L, and where ρ_g does not drop by more than 100 times - the simplified expression (34) of $V(x_0)$ is accurate.

This observation is extremely important for the practical utilisation of the described device. Indeed, as we already explained in the section 2.3.3, the total current measured by the device can be considered as the sum of a 'dark current' and a photocurrent. We saw that this approach was equivalent to the integration of the potential over the resistivity along the fiber. We will now make two different approximations:

- first, we will consider that the 'dark current' is independent of the light beam. This means that once the device is set, the user has to measure the current i_d when the fiber is in the dark or under the background homogeneous illumination (that remains when the beam is applied). This approximation can seem quite big when looking at the Fig 8, as this current is the integral under the curve, but we will see that the error is mainly corrected by the calibration of the device.

- second, as we work only with thin beams of light, we will consider that $V(x)$ for $x \in [x_0^-; x_0^+]$ is equal to $V(x_0)$. The photocurrent due to the light is thus given by:

$$I^{ph} = \frac{K\tau\mu_n e}{l_g} \Phi_0 \, \Delta x \, V(x_0) \tag{36}$$

Therefore, because of the similarity of the function $V(x_0)$ with the simplified profile (34), we can approximate the currents $i_0(x_0)$ and $i_L(x_0)$ with the following expressions:

$$i_0(x_0) = i_d + C_0\Phi_0\Delta x V_0^{eff}\frac{\cosh\dfrac{L-x_0}{\delta^{eff}}}{\cosh\dfrac{L}{\delta^{eff}}} \tag{37a}$$

$$i_L(x_0) = i_d + C_0\Phi_0\Delta x V_0^{eff}\frac{\cosh\dfrac{x_0}{\delta^{eff}}}{\cosh\dfrac{L}{\delta^{eff}}} \tag{37b}$$

where $C_0 = \frac{K\tau\mu_n e}{l_g}$ is a capacity times a length, in $Farad.m$, that depends only on the materials and geometry chosen for the fiber.

We show in the next section how these simplified expressions for the currents enable the device to retrieve the position x_0 of the beam.

2.5 Position detection: method and results

For a given beam of light, in order to determine δ^{eff} and the value of $C_0\Phi_0\Delta x V_0^{eff}$ we measured the total current i_0 or i_L flowing through the device. First in the dark, to obtain i_d, then for different positions x_0 of the beam. We then used Matlab to fit the simplified formulas (37) to the data. The figure 11 shows the typical quality of the fit.

Then, using a beam of known power (Φ_0), position (x_0) and width (Δx) we can measure the total current i_0 or i_L flowing through the device and thus, given the equation (37a) or (37b), determine the value of C_0:

$$C_0 = \frac{(i_0 - i_d)\cosh\dfrac{L}{\delta^{eff}}}{\Phi_0\Delta x V_0^{eff}\cosh\dfrac{L-x_0}{\delta^{eff}}} = \frac{(i_L - i_d)\cosh\dfrac{L}{\delta^{eff}}}{\Phi_0\Delta x V_0^{eff}\cosh\dfrac{x_0}{\delta^{eff}}} \tag{38}$$

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Current Vs position of the light beam in photodetecting fiber

Figure 11: Fitted simplified theory for the current $i_0(x_0)$ for an AST18 sample. $\delta^{eff} = 4.02$ cm

where i_d is the dark current, that has to be measured in absence of light, or under the background light. In the following we call $i_0^{ph} = i_0 - i_d$ and $i_L^{ph} = i_L - i_d$ the two photocurrents.

Knowing the value of C_0 is not sufficient to determine the characteristics $(\Phi_0, \Delta x, x_0)$ of an unknown beam from the measurement i_0 or i_L. Indeed, a thin beam localised near $x = 0$ can lead to the same value of i_0 than a larger one of the same power, but localised further on the fiber. It is based on that observation that the idea to measure two photocurrents $(i_0^{ph}$ and $i_L^{ph})$ is born. Indeed, as our first goal is to determine the position x_0 of a beam reaching the fiber, we now see that the ratio of those two currents gives us access to that position:

$$\frac{i_L^{ph}}{i_0^{ph}} = \frac{\cosh \dfrac{x_0}{\delta^{eff}}}{\cosh \dfrac{L - x_0}{\delta^{eff}}} \tag{39}$$

Finally, even if its width and power are unknown, the position x_0 of a beam can be determined, using the ratio (39):

$$x_0 = \frac{L}{2} + \frac{\delta^{eff}}{2} \ln \left(\frac{\dfrac{i_L^{ph}}{i_0^{ph}} - e^{-\frac{L}{\delta^{eff}}}}{1 - \dfrac{i_L^{ph}}{i_0^{ph}} e^{-\frac{L}{\delta^{eff}}}} \right) \tag{40}$$

The figure 12 displays the results of position detection for a sample of AST18-glass-core-fiber.

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Position detected Vs real position in photodetecting fiber

Figure 12: Position of the beam detected by an AST18-based device. The error made by the device is given and refers to the right scale.

These results are very satisfying, as the highest error in detection is 1.54 cm in this case. The length of the fiber is 42 cm so the highest error is only of 3.7% , where the average error (0.58 cm) is only of 1.4% of the length of the fiber.

This simple-structure device is therefore capable of detecting the position of a single beam of light with sufficient precision. However, it has to be kept in mind that, for the expression (40) to lead to the actual position x_0 of the beam, the value of δ^{eff} has to be well known by the user. Now, it has been showed in the section 2.4 that this value depends on the power of the beam (on its impact on the resistivity of the glass). The device thus has to be calibrated with a beam of power (and width) of the same order of magnitude than the expected beams to detect. This way, we have verified with Matlab that the error of detected position should never exceed a few centimeters. Obviously, the more precisely the power and width of the beam is known, the more accurate is the detection, especially around the middle of the fiber, where both currents i_0^{ph} and i_L^{ph} have quite important values. Devices for specific applications where the intensity and width of the beam to be detected would be known can thus be set up with this method. However, because of the impact of the light on the shape of the profile $V(x)$, the device is not able to detect anything else than a single beam. In fact, it is limited to the detection of the average position of the added light (compared to the 'dark' background). We will now describe a more elaborate structure, this time capable of detecting a more complex distribution of light $\Phi(x)$ with less restrictions.

3 Hybrid device: thin-film/solid-core structure

3.1 Establishing a light-independent non-uniform electric potential

Figure 13: A: SEM micrograph of a fiber with the new thin-film/solid-core structure. B: Experimental results (dots, the lines are added for clarity) of the voltage profile of a one-meter long fiber piece from panel A in the dark (in blue), and under a spot of white light (in red) and green light (in green) at the same location, same width and of similar intensity. C: schematic of the electrical connection to one fiber end.

3.1.1 Convex potential in the hybrid structure

Solid core fibers can hence support convex potential profiles that can be tuned using different glass compositions or fiber structure. When an optical signal is impingent on the fiber however, δ is no longer uniform as we considered earlier, since the glass resistivity is locally changed. This will in turn affect $V(z)$ that becomes an unknown function of the intensity distribution of the optical wave front. Moreover, thin-film structures are a more attracting system to work with in light of their better sensitivity and other advantages described in ref. [22]. To address these observations we propose an hybrid structure that enables to impose convex potential distributions that remain unchanged under illumination, accross a semiconducting thin-film that is used as the higher sensitivity detector. The fiber cross-section is shown in Fig 13A, where a CPC electrode contacts both a solid-core and a thin-film structure.

The equivalent circuit is represented in Fig 13C, where one can see that the two systems are in parallel. The drop of potential between the CPC channel and the metalic electrodes (both at the same potential) expressed in Eq (2) now becomes: $V(\frac{1}{R_c} + \frac{1}{R_c})$ where R_c and R_f are the resistance of a slab of cylindrical semiconducting solid-core and thin-film respectively, of length dz. This leads to a new differential equation:

$$\frac{\partial^2 V}{\partial z^2} = V \left(\frac{1}{\delta_c^2} + \frac{1}{\delta_f^2} \right) \approx \frac{V}{\delta_c^2} \tag{41}$$

since δ_c and δ_f , the characteristic parameters for the solid-core and the thin-film respectively, verify $\delta_c << \delta_f$ as can be anticipated from earlier results. The potential distribution is hence imposed by the solid-core system, while the current flowing through the photoconducting film can be measured independently, thanks to the different metallic electrodes contacting the solid-core and the thin-film structures. Similar boundary conditions can be imposed to the solid-core sub-system as before.

3.1.2 Experimental results

To verify our approach we fabricated a fiber integrating a structure with a CPC electrode in contact with both a solid-core of AST_{10} and a thin layer of the $As_{40}Se_{52}Te_8$ glass. This glass composition was chosen for its better thermal drawing compatibility with the polysulfone (PSU) cladding used here, which results in a better layer uniformity. Note that in this fiber, the metallic electrodes were embedded inside a CPC electrode. The conductivity of this assembly is still dominated by the high conductivity of the metal. The high viscosity of CPC in contact with the thin-film is however beneficial to maintain a layer of uniform thickness [35]. The contacts between the CPC electrodes and the glasses were found to be ohmic.

We reproduced the experiment described in section 1.2.3 to measure the potential drop between the CPC and the metallic electrodes along a one-meter long fiber piece. This time however, the experiment was done under three conditions: first in the dark, then when the fiber was illuminated, at the same location, by a white light source and then by a green (532 nm) LED, with intensity so that the generated photo-current in the thin-film by both illumination was almost the same. The results are shown in Fig 13B and illustrate the proposed concept very well. Indeed, since the green light is almost fully absorbed in the semiconducting layer [24], a significant change of thin-film resistivity (and hence a high photo-current) can be obtained while leaving δ_c, and thus the potential distribution across the layer, unchanged. White light on the other hand penetrates much deeper in the material and will change the conductivity of both the thin-film and the fiber core, changing δ_c and the voltage distribution. From these experiments we could extract the value $\delta_c = 143$ cm for this fiber system. This value is much larger than previous ones in solid-core structure because of the increase of S_{cpc} imposed by the new structure design. Note that we used green versus white light for this proof of concept, but many fiber parameters such as the glass composition or fiber geometry can be tuned to apply this approach to a wide range of radiation frequencies.

This new fiber system can now support a fixed potential profile $V(z)$ that can be varied by changing the applied boundary conditions. Given the Eq (41), one realizes that all possible profiles are a linear combination of the two functions:

$$V^I(z) = \frac{V}{\sinh\left(L/\delta_c\right)} \sinh h \left(\frac{L-z}{\delta}\right) \tag{42}$$

and

$$V^{II}(z) = \frac{V}{\sinh\left(L/\delta_c\right)} \sinh h \left(\frac{z}{\delta}\right) \tag{43}$$

obtained for the boundary conditions $V_0 = V$ and $V_L = 0$, and vice versa. A third independent voltage profile can also be imposed by applying a voltage between the CPC electrode and the electrode contacting the thin-film only, resulting in a nearly uniform potential $V(z) = V$, since δ_f is much larger than the fiber lengths considered. Hence, we can measure three independent photo-currents that result from the integration of the stimuli intensity profile modulated by these different voltage distributions, from which some axial information about σ_{ph} and hence Φ_0 can be extracted as we show below.

3.2 Resolving a single optical beam

3.2.1 Beam localization

Let us consider the case of an incident uniform light beam, with a rectangular optical wave front, at a position z_0 along the fiber axis, and with a width $2\Delta z$. It generates a photo-conductivity profile $\sigma_{ph}(z) = \sigma_{ph}$ if $z \in [z_0 - \Delta z, z_0 + \Delta z]$, and 0 otherwise. The generated current for each configuration can be derived, integrating over the illumination width and re-arranging the hyperbolic terms:

$$i_{ph}^I = \frac{2CV\sigma_{ph}}{\sinh\left(L/\delta_c\right)} \sinh h \left(\frac{L-z_0}{\delta_c}\right) \sinh h \left(\frac{\Delta z}{\delta_c}\right) \tag{44}$$

$$i_{ph}^{II} = \frac{2CV\sigma_{ph}}{\sinh\left(L/\delta_c\right)} \sinh h \left(\frac{z_0}{\delta_c}\right) \sinh h \left(\frac{\Delta z}{\delta_c}\right) \tag{45}$$

$$i_{ph}^{III} = 2CV\sigma_{ph}\Delta z \tag{46}$$

The first two currents are a function of the beam position which can be simply extracted by taking the ratio $r = \dfrac{i_{ph}^I}{i_{ph}^{II}}$ alleviating the dependence on the beam intensity and width. Much like we did with the first device after simplifying the potential profile expression in Eq (40), we can extract z_0 from the measurement of r through the relation:

$$z_0 = \frac{\delta_c}{2} \ln \left[\frac{e^{L/\delta_c} + r}{e^{-L/\delta_c} + r} \right] \tag{47}$$

The main difference is that this time, we do not need a δ^{eff} and we therefore do not have to limit ourselves to narrow, light-powered beams like we had to in section 2.4. This was

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experimentally verified by illuminating a one-meter long piece of the fiber shown in Fig 13, with a 1 cm width beam from a green LED, at different locations along the fiber length. The results are shown in Fig 14A where the straight line represents the experimental points of illumination of the fiber while the dots are the reconstructed positions from measuring the ratio of photo-currents r. The agreement between the experimental and measured positions is excellent, with errors made on the position smaller than ± 0.4 cm in the middle of the fiber.

Figure 14: Schematic of the illuminated fiber by a single optical beam and graph of the real position (black dashed line) and reconstructed position with error bars(blue dots) of an optical beam incident on a 1 m-long fiber at different positions. (B) Schematic of the illuminated fiber by a rectangular optical wave front. And graph of the real profile (black doted line) and reconstructed profile (blue dots) of a rectangular wave front incident on the same fiber.

3.2.2   Position error

Error over the beam position depends on a large number of parameters (Fiber length, δ_c, beam position and intensity, geometry etc...). Indeed, fluctuations of the photo-currents, that come from various sources [30-32], lead to variations on the ratio r, resulting in errors in the measured beam's position. To assess the resolution of our system, we first measured the dark current noise i_N, considered in good approximation to be the only source of noise here. We found it to be around 10 pA in our experimental conditions, using similar techniques as those explained in ref. [22]. This noise current is the same for configurations I and II given the symmetry of the system. Intuitively, when one measures a photo-current $i_{ph}^{I,II}$, its mean value lies within the segment defined by

$i_{ph}^{I,II} \pm i_N$. In a simple and conservative approach, we define the resolution of our system as the difference z_{0+} - z_{0-} of the two obtained positions z_{0+} and z_{0-} when the maximum error on the currents are made, i.e when r is given by $r_+ = \left(i_{ph}^I + i_N\right) / \left(i_{ph}^{II} - i_N\right)$ and $r_- = \left(i_{ph}^I - i_N\right) / \left(i_{ph}^{II} + i_N\right)$ respectively. These error bars are represented in the graph of Fig 14A. The resolution found is sub-centimeter, corresponding to two orders of magnitude smaller than the fiber length. This is to the best of our knowledge the first time that a beam of light can be localized over such an extended length and with such a resolution, using a single one dimensional distributed photodetecting device requiring only four points of electrical contact.

3.2.3   Other beam characteristics

The beam position is not the only spatial information we can reconstruct with this system. Indeed, the ratio of i_{ph}^{II} and i_{ph}^{III} allows us to reconstruct Δz as z_0 is known, by measuring the ratio $\dfrac{\sinh(\Delta z / \delta_c)}{\Delta z / \delta_c}$. This also enables to evaluate σ_{ph}, using i_{ph}^{III} , and hence reconstruct the associated beam intensity . In Fig 13B we show the experimental illumination profile of a green LED light (black dashed line, centered at 43 cm, width 18 cm, with a conductivity $\sigma_{ph} = 6\sigma_{dark}$) and the reconstructed profile from current measurements (blue data points, centered at 43.5 cm, width 24 cm and $\sigma_{ph} = 4.7\sigma_{dark}$). The positioning is very accurate as expected from the results above, while a slightly larger width is measured. This error is due to the large value of δ_c compared to Δz, which results in a ratio of i_{ph}^{II} to i_{ph}^{III} more sensitive to noise than the ratio of i_{ph}^I over i_{ph}^{II} . It is however clear from discussions above that the fiber system can be designed to have a much better resolution for different beam width ranges, by tuning δ_c to smaller values.

Also under study is the integration time required for this system. The speed at which we can vary the potentials depends on the bandwidth associated with the equivalent circuit, taking into account transient current effects in amorphous semiconductors. In this proof-of-concept, measurements were taken under DC voltages applied, varying the boundary conditions after transient currents are stabilized (typically after a few seconds). Novel designs, especially fibers where the semiconducting material has been crystallized through a post-drawing crystallization process [14], and integrating rectifying junctions that have proven to have several kHz of bandwidth [15], could result in significant improvement in device performance and speed.

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3.3 Extracting axial information from multiple incoming beams

When more than one beam are incident on the fiber, each one brings a set of three unknown parameters to be resolved (its axial position, width and power). Since our detection scheme provides three independent photo-currents, some prior knowledge on the stimuli is then required to localize each beam along the fiber axis. For example, we can localize two similar illumination events (with approximately same width and power), that are incident at different axial positions.

3.3.1 Two identical beams

Let us consider the simpler case where two such beams impinging the fiber have a width $2\Delta z$ much smaller than the solid-core characteristic length δ_c, so that

$$\frac{\sinh(\frac{\Delta z}{\delta_c})}{\frac{\Delta z}{\delta_c}} \approx 1 \tag{48}$$

They each generate a photo-conductivity σ_{ph} at their positions $z_1 < z_2$. The photo-currents measured are the sum of the measured currents with individual beams. Defining $Z_m = \frac{z_1 + z_2}{2}$ and $Z_D = \frac{z_2 - z_1}{2}$, we can derive:

$$i_{ph}^{I} = \frac{4CV\sigma_{ph}}{\sinh(L/\delta_c)} \sinh h \left(\frac{\Delta z}{\delta_c}\right) \sinh h \left(\frac{L - Z_m}{\delta_c}\right) \sinh h \left(\frac{Z_D}{\delta_c}\right) \tag{49}$$

$$i_{ph}^{II} = \frac{4CV\sigma_{ph}}{\sinh(L/\delta_c)} \sinh h \left(\frac{\Delta z}{\delta_c}\right) \sinh h \left(\frac{Z_m}{\delta_c}\right) \sinh h \left(\frac{Z_D}{\delta_c}\right) \tag{50}$$

$$i_{ph}^{III} = 4CV\sigma_{ph}\Delta z \tag{51}$$

Following the same approach as in the single beam case, we can reconstruct Z_m and Z_D, and hence z_1 and z_2. On Fig 15A, we show the experimental illumination of a fiber with two identical beams of width 6 cm from the same green LED (dashed black curve) at positions 54 cm and 75 cm. The blue dots represent the reconstructed beam position, with measured position 51 $\pm$ 3 cm and 78 $\pm$3 cm for the two beams. The error on the positions were computed in a similar fashion as before.

3.3.2 Three identical, regularly-spaced beams

An optical signal made out of three beams requires even more additional constraints to be resolved. For example, three similar beams equidistant from one to the next can be detected and localized with our system. Indeed, here again only two unknowns have to be found: the central beam position and the distance between two adjacent beams. The derivation of the algorithm to extract these positions from the different current measurements is very similar to what has been derived above. In Fig 15B we show experimental results of the localization of three incoming beams of same width ($\Delta z = 6$

Figure 15: (A) Schematic: photodetecting fiber illuminated by two similar optical beams. Graph: position measurements of the two beams. In black doted line is the conductivity profile generated by the two incoming beams while the blue dots are the reconstructed positions with the error bars. (B) Schematic: photodetecting fiber illuminated by three similar optical beams. Graph: position measurements of the three beams. In black doted line is the conductivity profile generated by the three incoming beams while the blue dots are the reconstructed positions with the error bars.

cm) and intensity (generating a photo-conductivity $\sigma_{ph} = 8.5\sigma_{dark}$) at positions $z_1 = 35.5$ cm, $z_2 = 55.5$ cm, and $z_3 = 75.5$ cm. The generated conductivity pattern is represented by a black doted line on the graph. The reconstructed positions from photo-current measurements were 30 ±4 cm, 51.5 ± 4 cm and 73 ± 4 cm, in very good agreement with the real beams locations. Note that in these two multiple beams cases, we could only extract the position of the beams but not their intensity nor width. If we knew the width of each beam however, we would be able to extract the position and intensity assuming that this intensity is the same.

Conclusion

In conclusion, axially resolved optical detection was achieved in an axially symmetric multimaterial fiber. Two fiber architectures that combine insulating and semiconducting domains together with conductive metallic and polymeric materials was demonstrated. Both architectures support a convex electric potential profile along the fiber axis that can be varied by changing the boundary conditions. The simplest structure can under restrictive conditions localize a single beam of light but its behavior depends heavily on the measured light itself which limits it to very specific applications. A more elaborate hybrid device displays much more stable properties when the materials and the internal geometry are carefully chosen in regard of the light to be detected. As a result, the position, width and the intensity of an arbitrary incoming rectangular optical wavefront can be reconstructed. Under given constraints, two and three simultaneously incident beams can also be spatially resolved. The ability to localize stimuli along an extended fiber length using simple electronic measurement approaches and with a small number of electrical connections, presents intriguing opportunities for distributed sensing.

Appendix A: δ calculation

Glass core geometry

We consider a fiber where a glass core is contacted by two opposed electrodes running along the length of the fiber (Fig 16):

Figure 16: The glass core geometry for the photodetecting fiber

The radius of the core is r_g, while t_{cpc} is the thickness of the CPC electrode and w_{cpc} its width (w_{cpc} is exaggerated in Fig 16). Neglecting the curvature of the electrode, the cross section of one of the electrodes has a surface $S_{cpc} = t_{cpc} \, w_{cpc}$.

For the calculation we will approximate the contact between each electrode and the core as being located on one single point. This is correct as long as w_{cpc} remains small compared to r_g. This way, the resistance R_g is given by:

$$R_g = \int_{-r_g}^{r_g} \rho_g \frac{dh}{2 \, dx \, r_g \, cos\Theta} \tag{52}$$

where h and Θ are given by the Fig 17, and ρ_g is the resistivity of the glass.

Figure 17: Elements for the calculation

As $h = r_g sin\Theta$, then $dh = r_g cos\Theta d\Theta$ and so:

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$$R_g = \rho_g \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \frac{d\Theta}{2\,dx} = \rho_g \frac{\pi}{2\,dx} \tag{53}$$

It is remarkable that the resistance of a cylinder connected at two diametrically opposite points does not depend on the radius of this cylinder. This way a smaller glass core could be used without changing the resistance, but allowing a higher electric field in the glass for a same voltage applied.

The resistance of a CPC electrode for a length dx of fiber is $R_{cpc} = \rho_{cpc} \frac{dx}{S_{cpc}}$, where ρ_{cpc} is the resistivity of the CPC. Finally, for a glass core geometry, δ is given by:

$$\delta = \sqrt{\frac{R_g}{R_{cpc}}}\,dx = \sqrt{\frac{\rho_g}{\rho_{cpc}} \frac{\pi}{2} S_{cpc}} \tag{54}$$

And so, if α is the draw-down ratio, i.e. the ratio between the diameters of the preform and of the fiber and if S_{cpc}^0 is the initial surface of the cross section of the CPC electrode in the preform, then we have $S_{cpc} = \frac{S_{cpc}^0}{\alpha^2}$. This leads us to the final result for δ:

$$\delta_{core} = \frac{1}{\alpha} \sqrt{\frac{\pi}{2} \frac{\rho_g}{\rho_{cpc}} S_{cpc}^0} \tag{55}$$

Glass layer geometry
We consider now a fiber where a glass layer is contacted by two opposed electrodes running along the length of the fiber (Fig 18):

Figure 18: The glass layer geometry for the photodetecting fiber

The radius at which the layer is deposited is r_g, while t_g is its thickness. t_{cpc} is the thickness of the CPC electrode and w_{cpc} its width (w_{cpc} and t_g are exaggerated in Fig 18). Neglecting the curvature of the electrode, the cross section of one of the electrodes has a surface $S_{cpc} = t_{cpc}\,w_{cpc}$.

For the calculation we will again approximate the contact between each electrode and the layer as being located on one single point. This is correct as long as w_{cpc} remains

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small compared to r_g. We will also always consider that $t_g << r_g$, which is right, as r_g is $100\mu m$ minimum, while t_g is at most a few micrometers. This way, the resistance R_g is given by:

$$R_g = \frac{1}{2} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \rho_g \frac{r_g \, d\Theta}{dx \, t_g} \tag{56}$$

where Θ is defined on the figure 19, and the factor $\frac{1}{2}$ takes into account the fact that the integral on Θ leads only to the resistance of half of the layer.

Figure 19: Elements for the calculation

The resistance of the glass for a length dx is then:

$$R_g = \rho_g \frac{\pi r_g}{2 dx t_g} \tag{57}$$

The resistance of a CPC electrode for a length dx of fiber is $R_{cpc} = \rho_{cpc} \frac{dx}{S_{cpc}}$. Finally, for a glass layer geometry, δ is given by:

$$\delta = \sqrt{\frac{R_g}{R_{cpc}}} dx = \sqrt{\frac{\pi}{2} \frac{\rho_g}{\rho_{cpc}} \frac{r_g S_{cpc}}{t_g}} \tag{58}$$

And so, if α is the draw-down ratio, i.e. the ratio between the diameters of the preform and of the fiber and if S_{cpc}^0 is the initial surface of the cross section of the CPC electrode in the preform, then we have $S_{cpc} = \frac{S_{cpc}^0}{\alpha^2}$. Besides, if r_g^0 and t_g^0 are respectively the radius and the thickness of the glass layer in the preform, then $\frac{r_g}{t_g} = \frac{r_g^0}{t_g^0}$. This leads us to the final result for δ:

$$\delta_{layer} = \frac{1}{\alpha} \sqrt{\frac{\pi}{2} \frac{\rho_g}{\rho_{cpc}} \frac{S_{cpc}^0 r_g^0}{t_g^0}} \tag{59}$$

Appendix B: Stress and resistivity of the CPC

In the section 3.3.2, we have obtained, for both studied geometries, the expression of δ. As δ is the main parameter of the system, it is important for us to control its value precisely. We have already shown that δ is proportionnal to the diameter of the fiber, and that we can use different glasses, with different resistivities ρ_g (Fig 10). As the cross-section S^0_{cpc} of the CPC electrode in the preform is more or less always the same, the last parameter is ρ_{cpc}.

As already mentionned, the Conductive PolyCarbonate has been used as a metal in different projects of the group over the past few years. However no data on the hypothetical evolution of its resistivity with the draw parameters (temperature, stress) was available when we started to use it in our photodetecting fibers. It is only after having recurrent problem in connecting several fiber samples that we decided to study the variations of ρ_{cpc}. This study is however incomplete and further investigation is needed, but the first results were very interesting and we give them here.

The electrical conduction inside the CPC is due to the carbon particles: their concentration is above the percolation level, and so the CPC is conducting. But during the draw, if the temperature is low enough, the carbon particles might not flow fast enough to ensure the electrical conduction in the final fiber.

Figure 20: For the low temperature draw, as the stress endured by the fiber increases, ρ_{cpc} increases of several orders of magnitude.

In order to verify whether that phenomenon occurs or not, we drew a simple fiber where a layer of CPC is surrounded by insulating cladding, and studied the resistivity of different samples, depending on the stress they endured during the draw. We did so for two different fibers: in the first one, the insulating polymer was PolyCarbonate (PC), and the temperature during the draw was 235 degrees. In the second one, the cladding was PolySulfonide (PSU), and the draw temperature was 272 degrees.

For the PSU-cladding fiber, no sensible variation of the resistivity was observed: ρ_{cpc} remained comprised between 0.55 and 1 Ohm.m for fibers that had endured stress ranging

from 100 to 600 $g.m^{-2}$. However, for the PC-cladding fiber, huge variation of ρ_{cpc} are witnessed as the stress varies (Fig 20)

It thus seems that when the temperature of the draw is low enough, there is a transition conductive $\rightarrow$ insulating due to the stress applied on the fiber. It has been demonstrated that this transition was not due to the diminution of diameter of the fiber often linked with the increase of stress because some of the finest fibers have endured a very low stress and conduct very well the current. However, in our draws, the increase of stress is always linked to an increase of the capstan speed. This transition might be due to the fact that carbon particles do not have enough time to reorganize within the insulating matrix when the capstan speed is too high or the temperature is too low.

This study, even incomplete, has enabled us to demonstrate a metal $->$ insulating transition in the CPC during the draw process. There is no reference to such a transition in the existing litterature, and an exhaustive study of the variations of ρ_{cpc} is needed to understand the underlying mechanism occuring within the CPC during the draw.

During this project, as the fibers were all based on PSU cladding, the draw temperature was always high enough for this transition not to happen. However, if this transition was well understood and the stress well controled during the draw, we could play on the value of ρ_{cpc}, via the stress during the draw, to modify the final value of δ.

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