M. Skorobogatiy, B. Ung, A. Mazhorova, M. Rozé, A. Dupuis, "Plastic fibers for terahertz wave guiding," ECOC 2011, Tu.6.LeCervin.1, Geneva, Switzerland, September 18-22, 2011.

Plastic fibers for terahertz wave guiding

Bora Ung, Alexandre Dupuis, Mathieu Rozé, Anna Mazhorova, Frédéric Désévédavy,

Maksim Skorobogatiy

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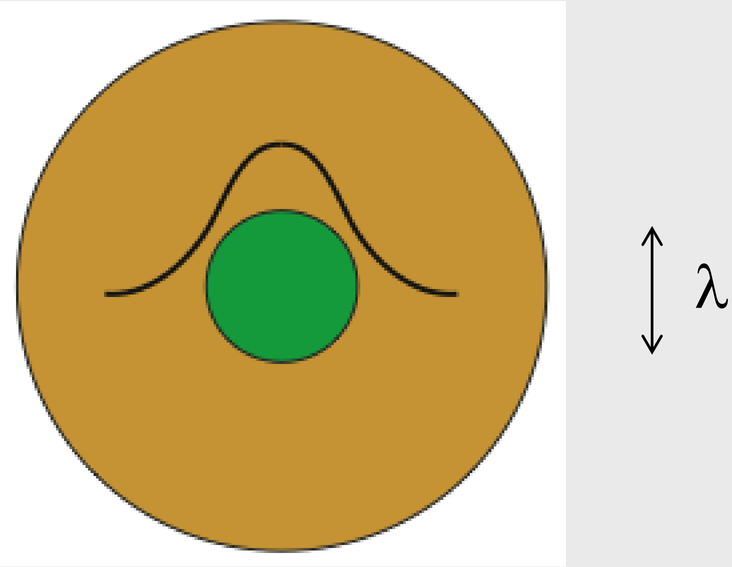
Standard solid core TIR fiber in THz

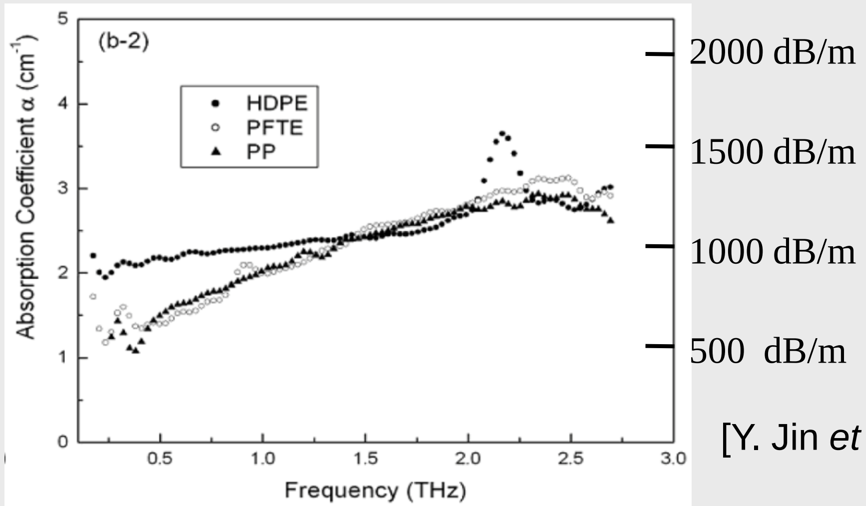
Terahertz: ν = 0.1-10 THz <=> λ = 3000-30 μm

Total Internal Reflection solid-core fibers:

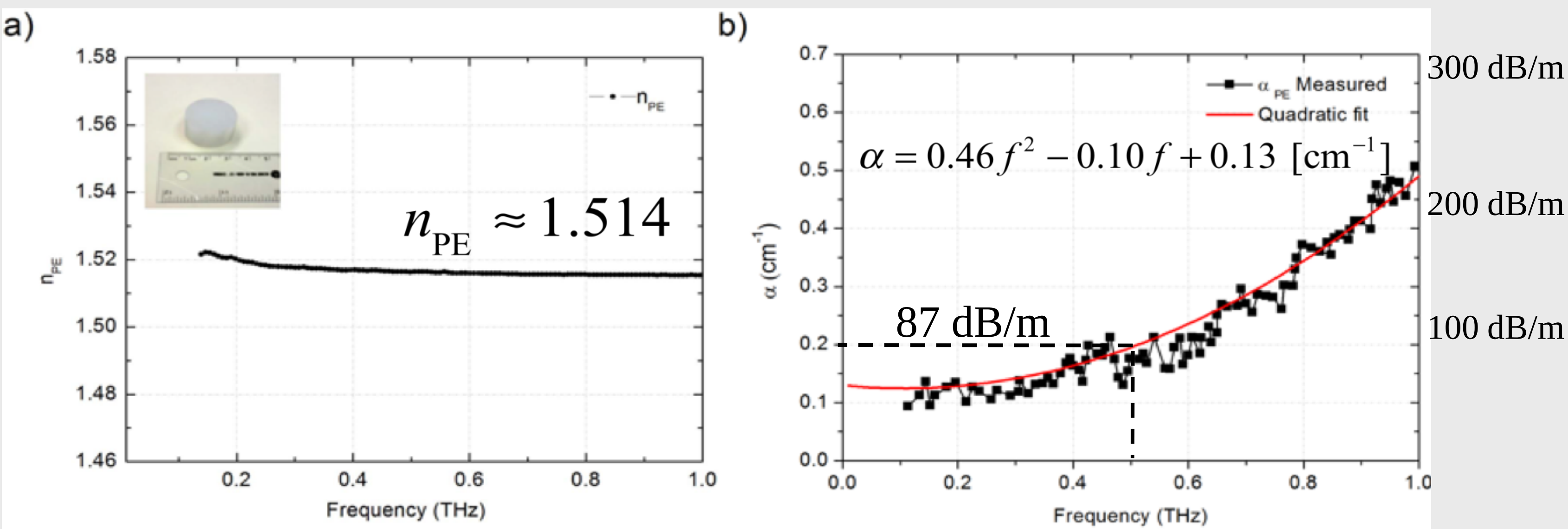
- Pros: Insensitive to environment (humidity, dust, etc.)
- Cons: High loss, high group velocity dispersion



Bulk polyethylene (PE) THz optical properties

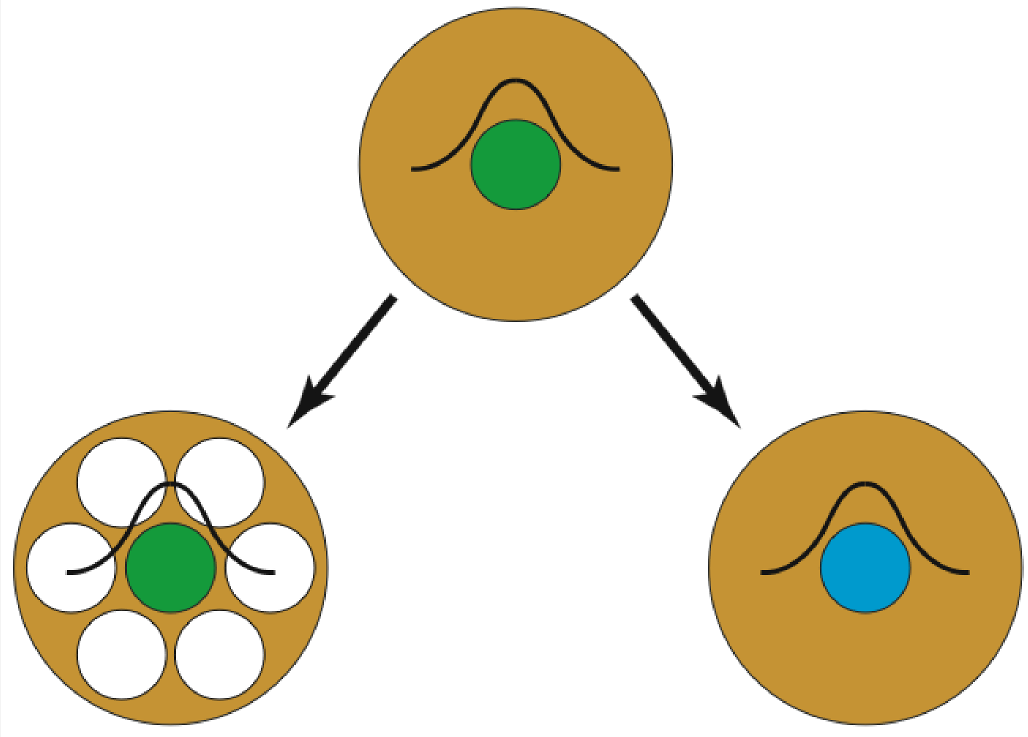


[Y. Jin *et al.*, *J Kor. Phys. Soc*. **49** (2006)]



[A. Mazhorova, J. Gu, A. Dupuis, M. Peccianti, O. Tsuneyuki, R. Morandotti, H. Minamide, M. Tang, Y. Wang, H. Ito, and M. Skorobogatiy, '' Composite THz materials using aligned metallic and semiconductor microwires, experiments and interpretation,'' *Opt. Express*, 18 (2010)]

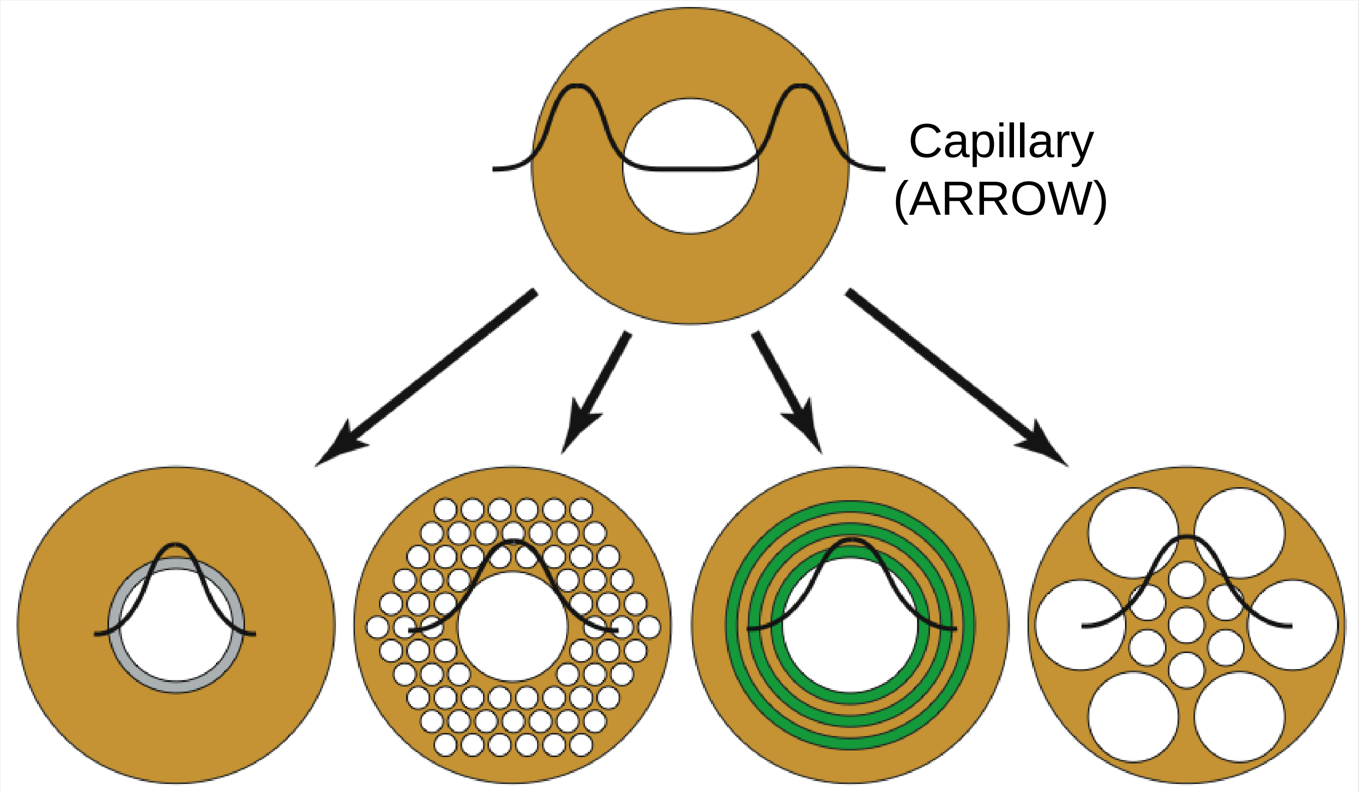
Lowering absorption loss in TIR fibers



Lower loss dielectrics by chemistry or composite materials

Holes filled with dry gas

Lowering absorption loss in fibers. Hollow core guidance.



Metallized capillaries

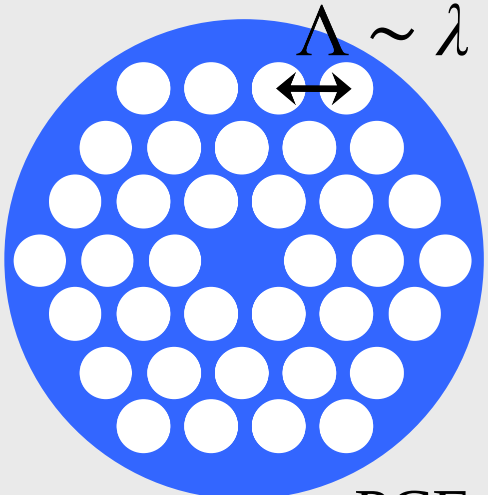
Porous TIR fibers

Photonic Bandgap Fibers

Plastic fibers for terahertz waves studied in our group

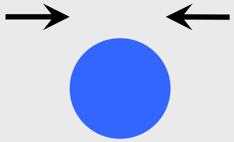
SOLID CORE

$\Lambda \sim \lambda$

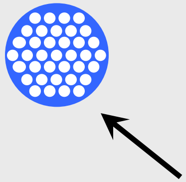


PCF

$d < \lambda$



subwavelength core



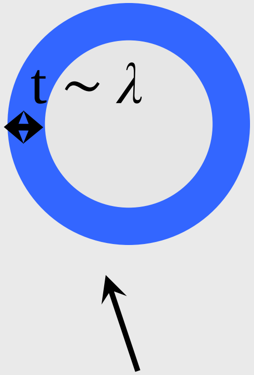
porous core

$\Lambda << \lambda$

HOLLOW CORE

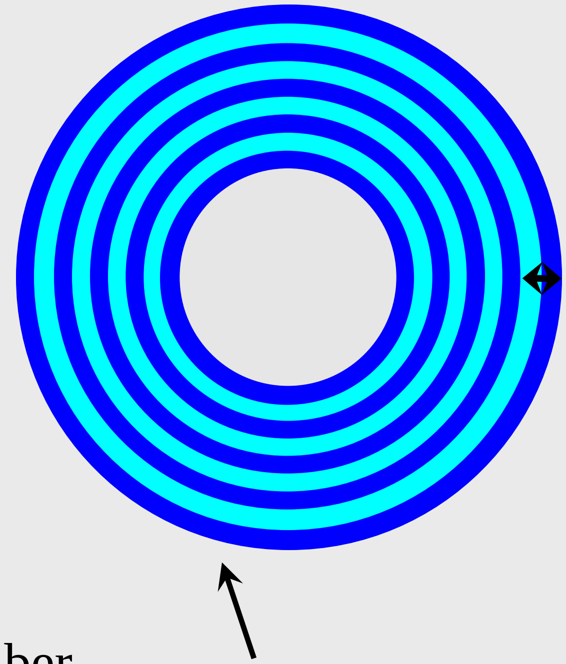
$$\alpha \sim \frac{1}{r_{core}^{3} \nu^{2}}$$

$t \sim \lambda$



ARROW fiber

$\Lambda \sim \lambda$



PBG fiber

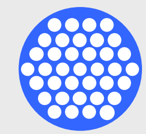
Subwavelength dielectric fibers

solid core

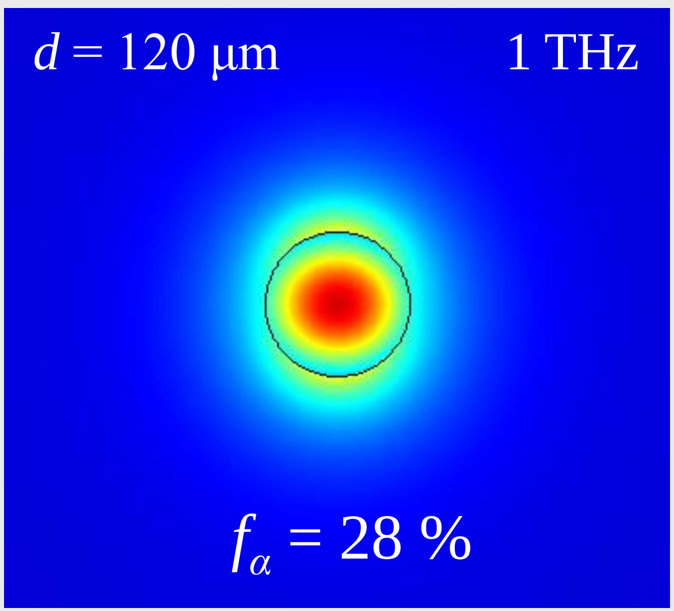
$\rightarrow \quad \leftarrow d < \lambda$

porous core

$\Lambda << \lambda$

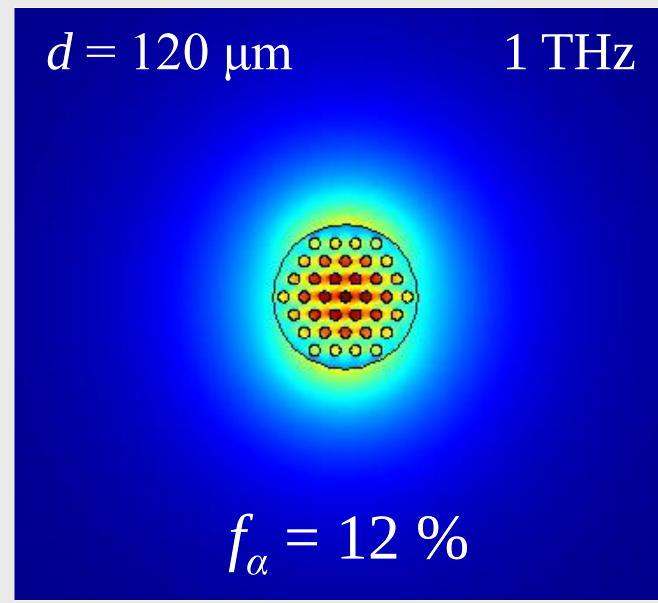


$\rightarrow \quad \leftarrow d < \lambda$



$$f_\alpha = \frac{\mathrm{Re}(n_{mat}) \cdot \int_{mat} |\boldsymbol{E}|^2 dA}{2\int_{total} S_z dA}$$

$$S_z = \frac{1}{2}\mathrm{Re}(\boldsymbol{E} \times \boldsymbol{H}^*) \cdot \hat{z}$$

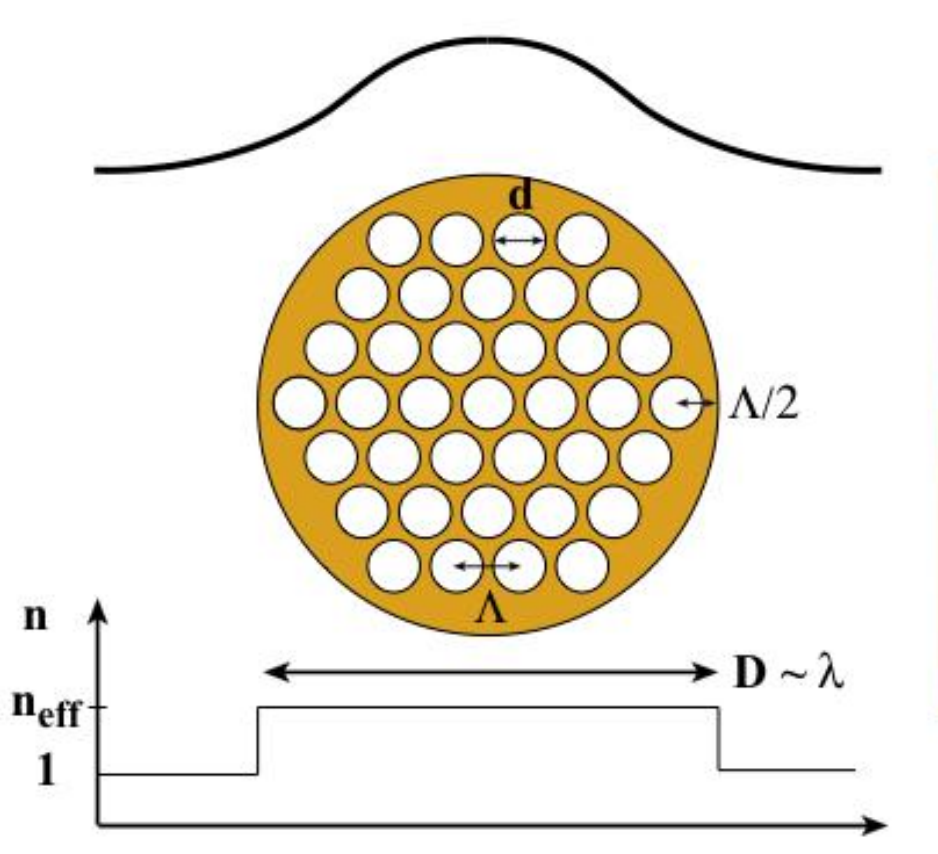


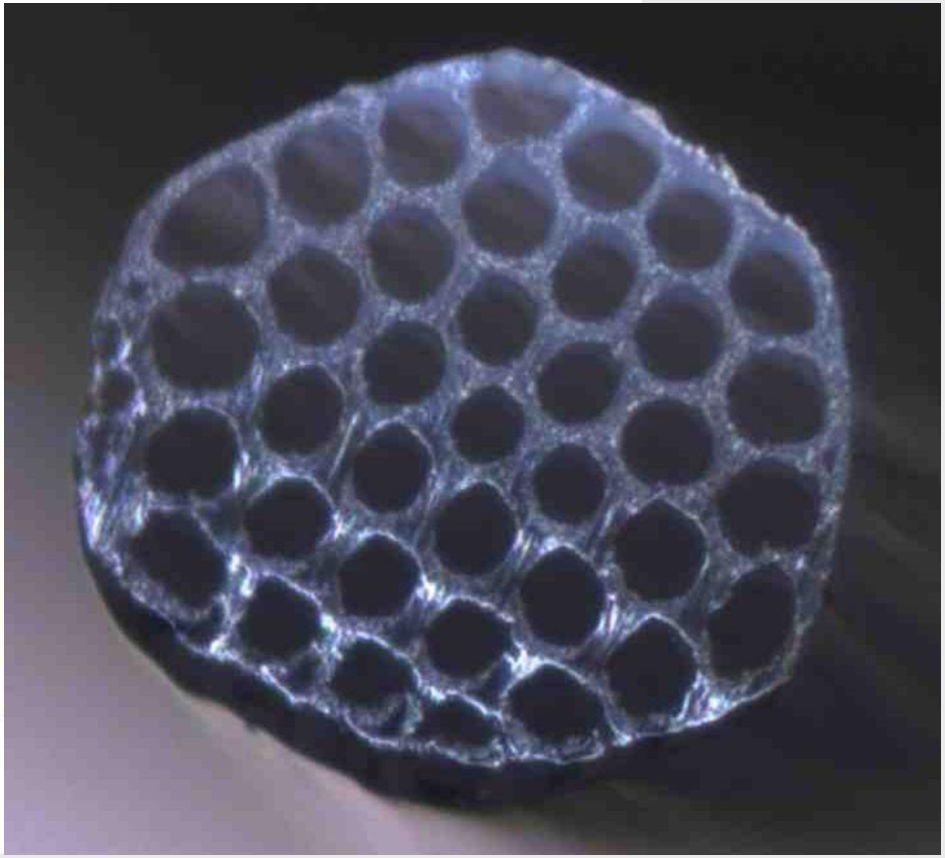
A. Hassani, A. Dupuis, and M. Skorobogatiy, "Low Loss Porous Terahertz Fibers Containing Multiple Subwavelength Holes," *Appl. Phys. Lett*. **92**, 071101 (February 19, 2008).

Subwavelength porous fibers

Lower loss dielectrics by composite materials

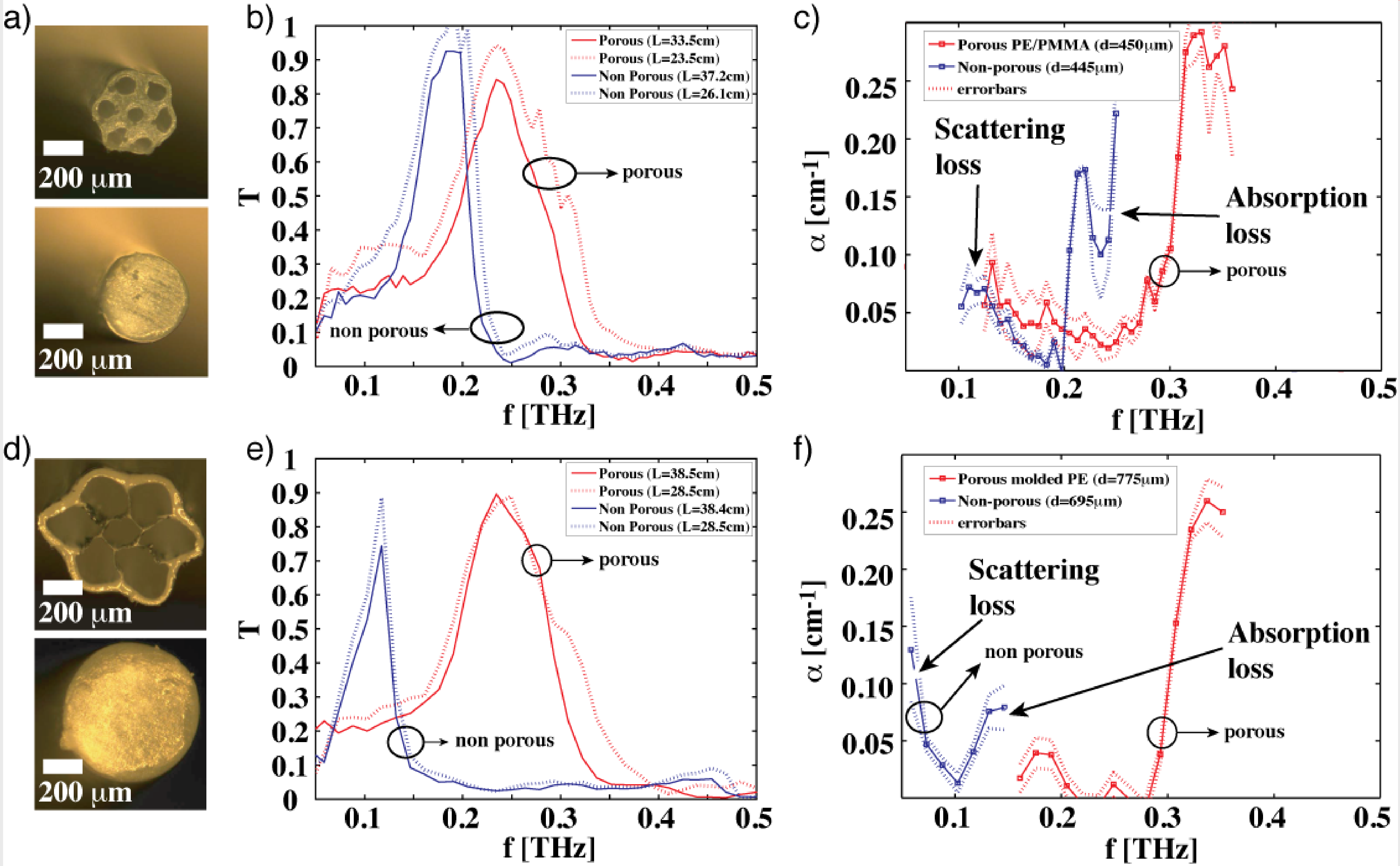
Guidance by total internal reflection





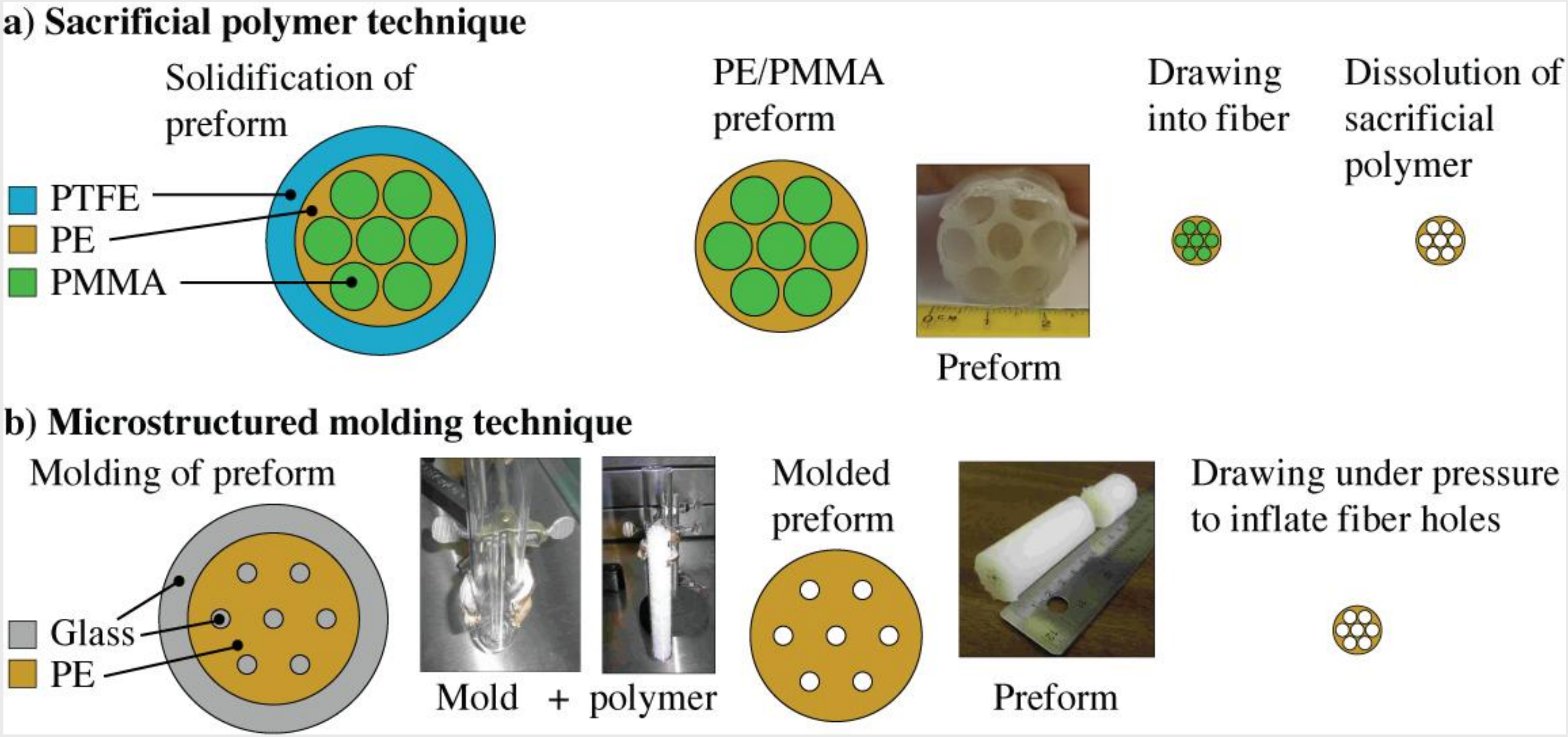
A. Hassani, A. Dupuis, and M. Skorobogatiy, "Low Loss Porous Terahertz Fibers Containing Multiple Subwavelength Holes," *Appl. Phys. Lett*. **92**, 071101 (February 19, 2008).

Transmission and losses of porous fibers



[A. Dupuis, A. Mazhorova, F. Desevedavy, M. Roze, M. Skorobogatiy, "Spectral characterization of porous dielectric subwaveleng THz fibers fabricated using a microstructured molding technique," *Opt. Express* **18**, 13813-13828 (2010)]

Fabrication of porous fibers

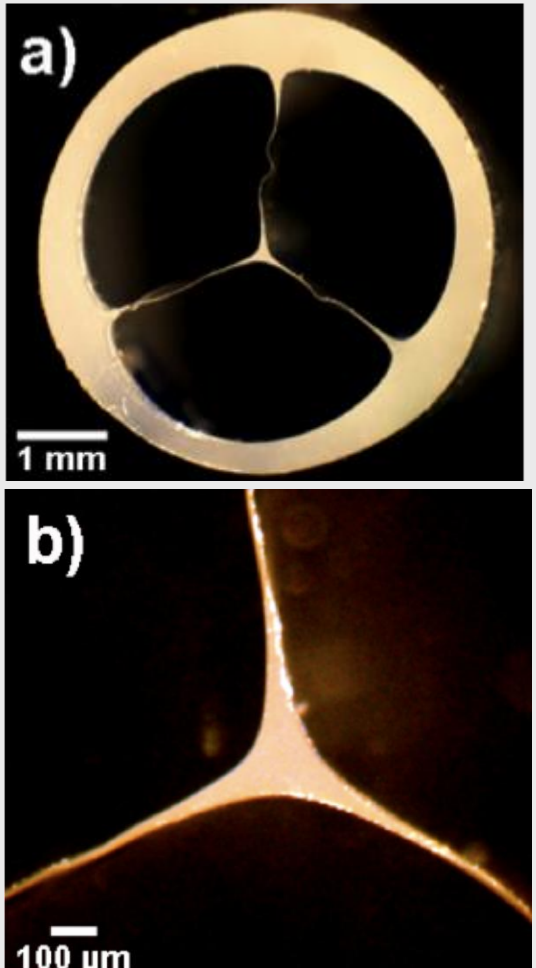


[A. Dupuis, A. Mazhorova, F. Désévédavy, M. Rozé and M. Skorobogatiy, *Opt. Express*, **18** (2010)]

Packaging of subwavelength fibers: encapsulation within a protective tube

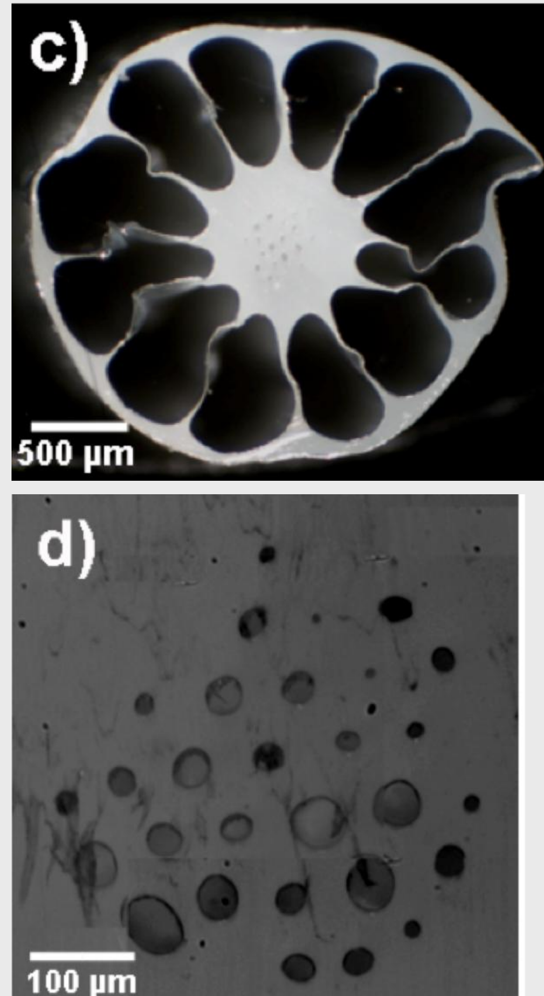
solid core | porous core

OD = 5.1 mm



d_{core} ~ 150 μm

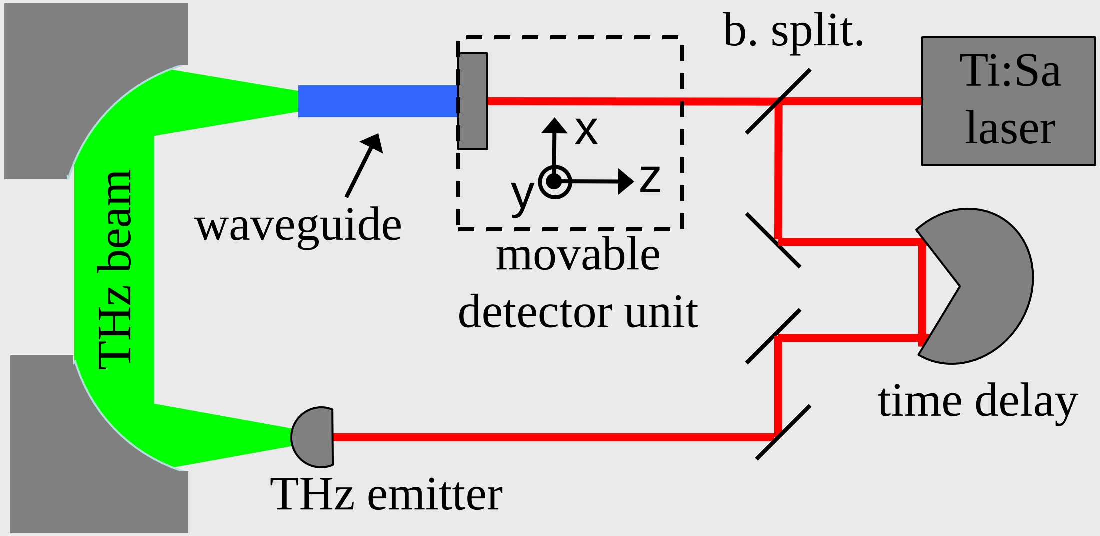
OD ~ 3.0 mm

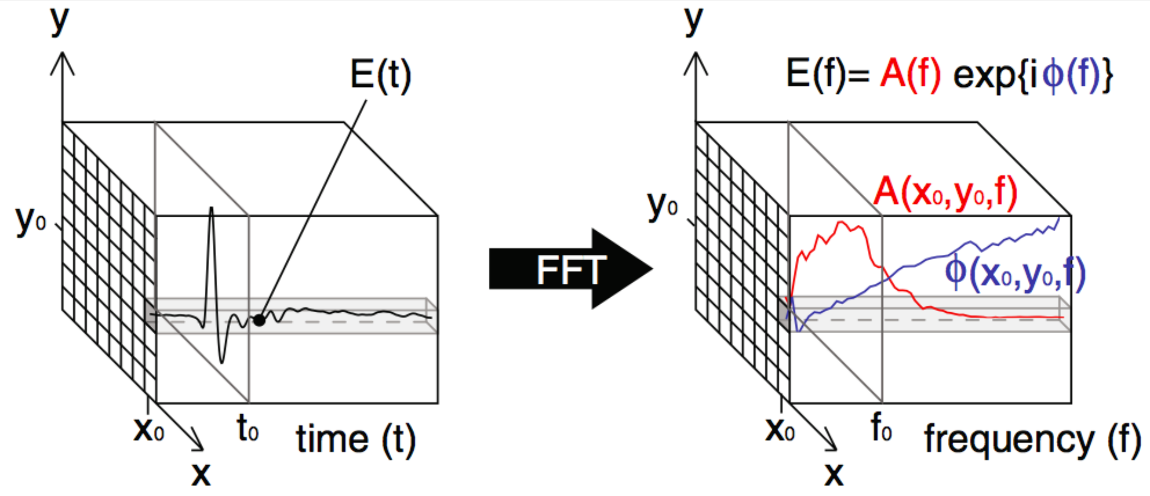


d_{core} ~ 900 μm

[M. Roze, B. Ung, A. Mazhorova, M. Walther, M. Skorobogatiy, "Suspended core subwavelength fibers: towards practical designs for low-loss terahertz guidance," Optics Express **19**, 9127 (2011)]

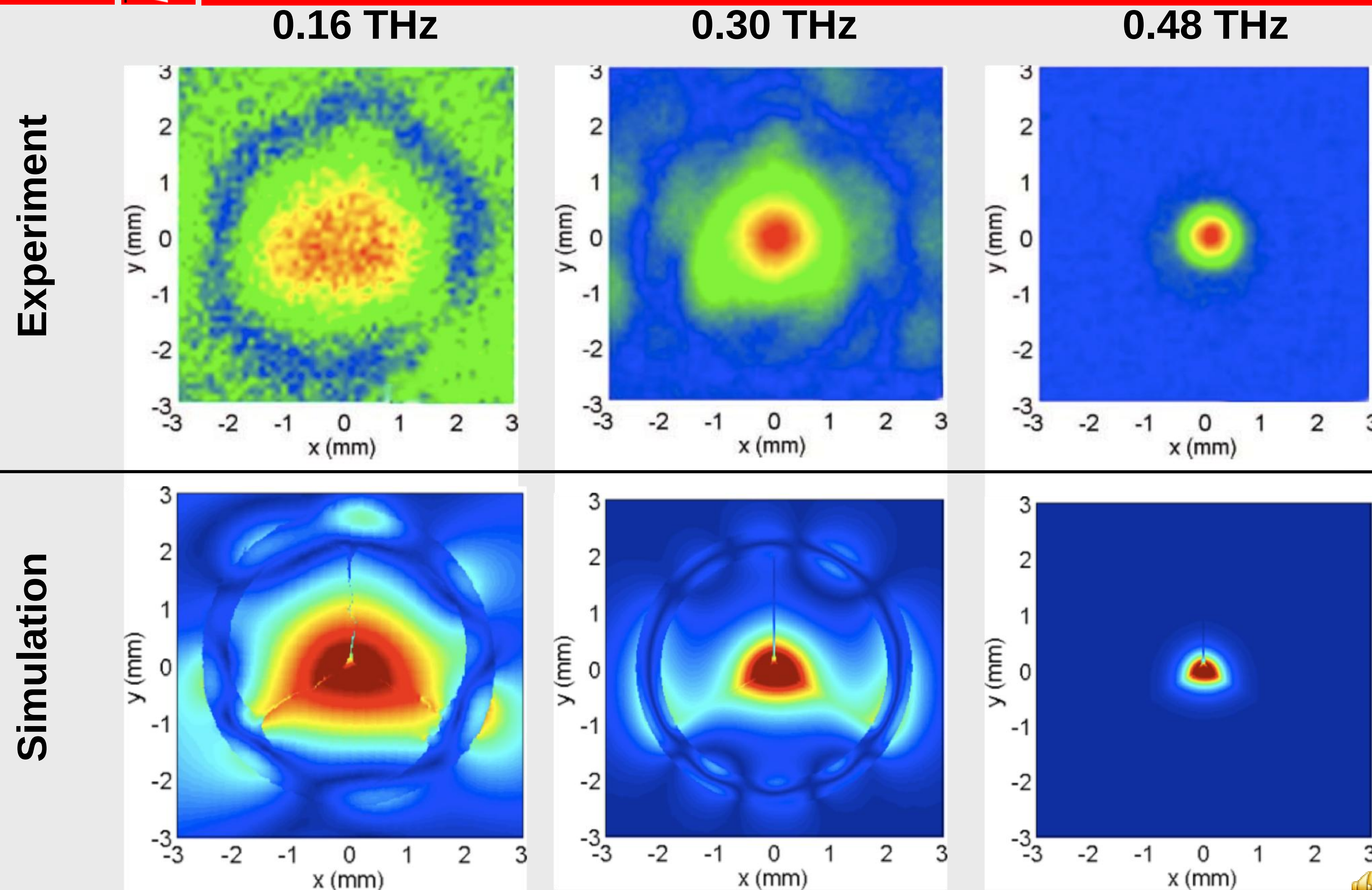
THz near-field imaging setup





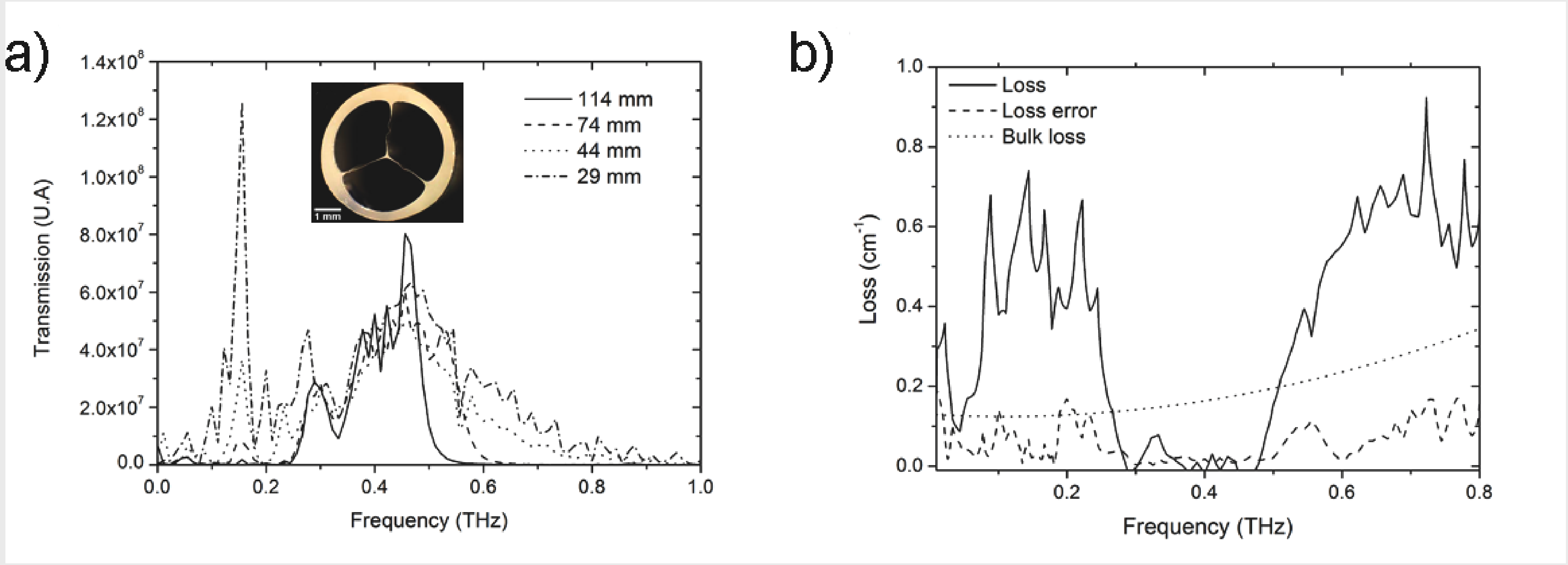
[M. Walther, and A. Bitzer, "Electromagnetic Wave Propagation Close to Microstructures Studied by Time and Phase-Resolved THz Near-Field Imaging," *J Infrared Milli Terahz Waves* (2011)]

THz near-field imaging of output profile for the suspended solid core fiber



[M. Rozé, B. Ung, A. Mazhorova, M. Walther and M. Skorobogatiy, *Opt. Express*, **19** (2011)]

Suspended fibers: transmission spectrum and propagation losses

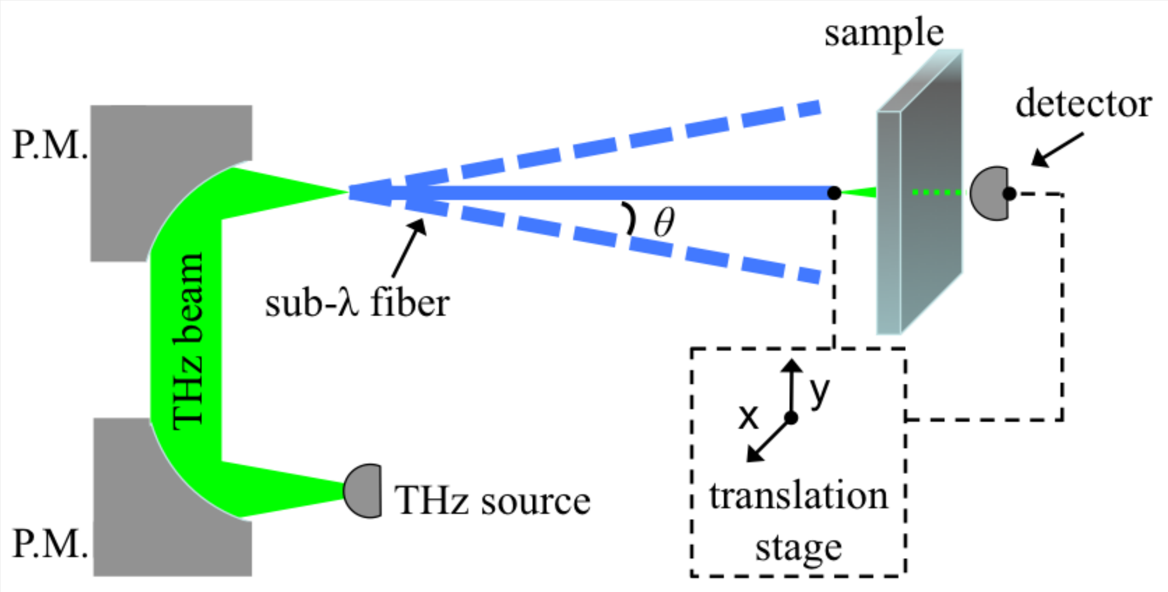


min loss ≤ 0.02 cm^{-1}

[M. Rozé, B. Ung, A. Mazhorova, M. Walther and M. Skorobogatiy, *Opt. Express*, **19** (2011)]

Examples of devices based on subwavelength dielectric fibers: near field imaging

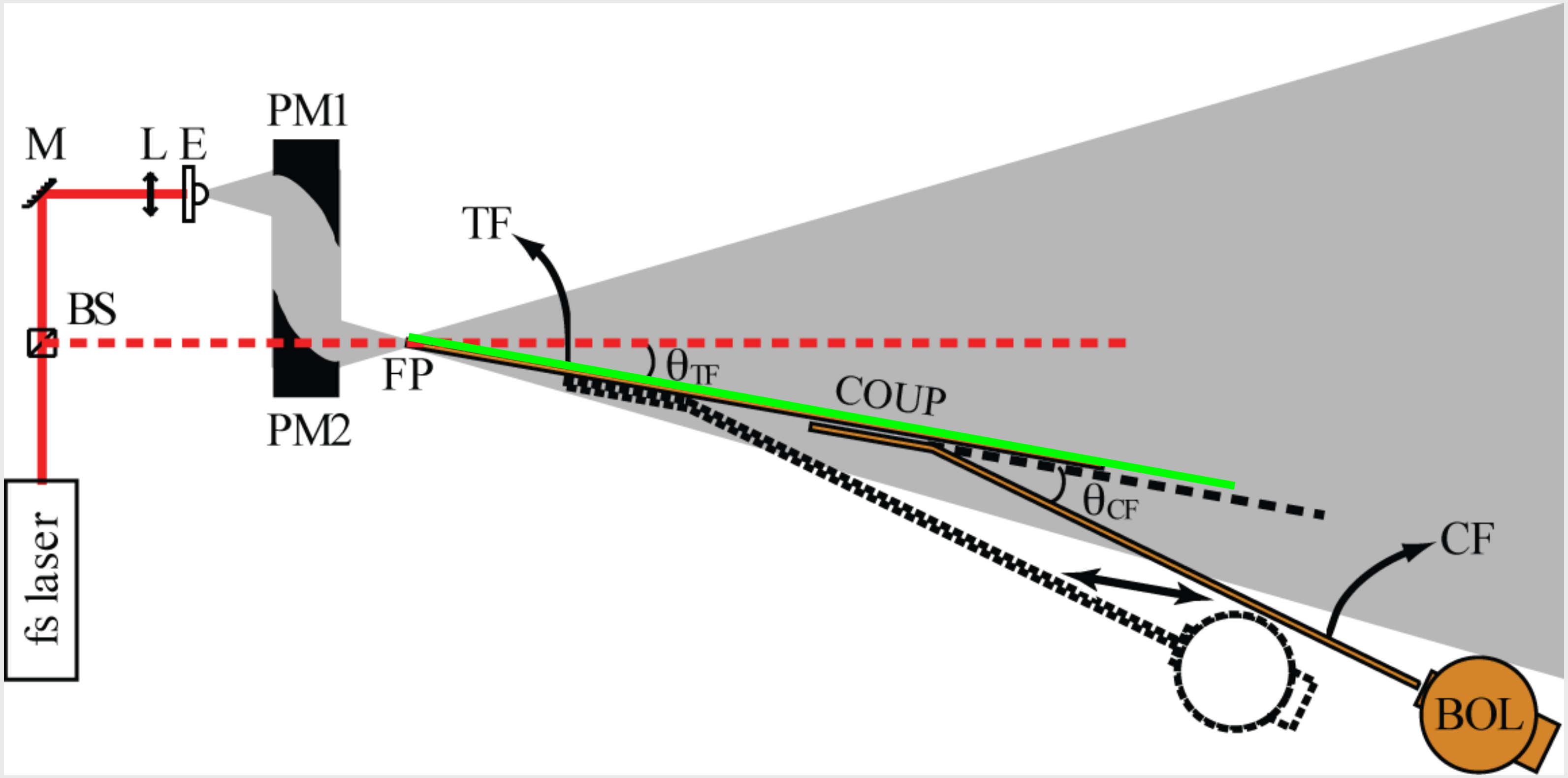
Fiber-scanning THz imaging technique.



[J. Lu, C. Chiu, C. Kuo, C. Lai, H. Chang, Y. Hwang, C. Pan, and C. Sun, *Appl. Phys. Lett.*, **92** (2008)]

Examples of devices based on subwavelength dielectric fibers: non-destructive cut back

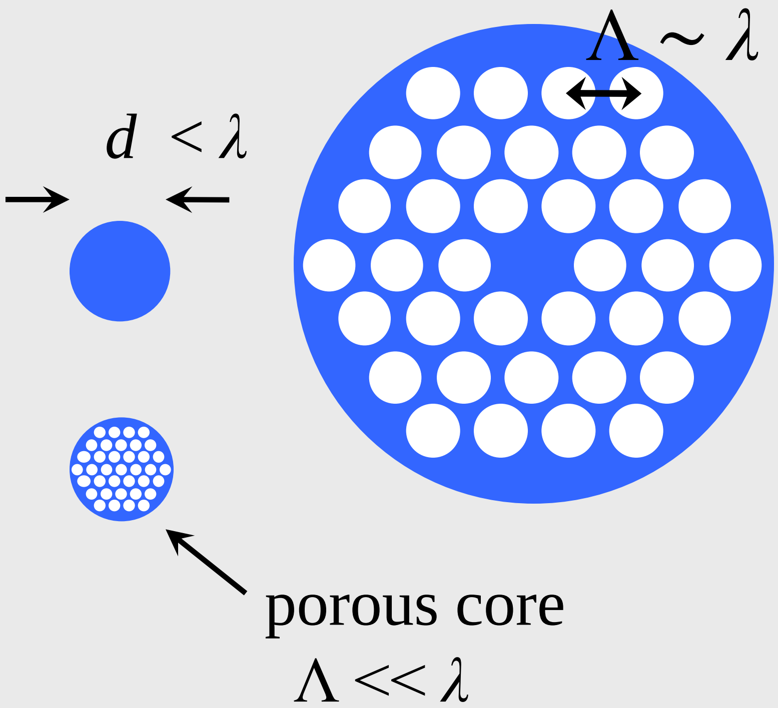
Fiber-based directional coupler for non-destructive cutback technique.



[A. Dupuis, J.-F. Allard, D. Morris, K. Stoeffler, C. Dubois, and M. Skorobogatiy, "Fabrication and THz loss measurements of porous subwavelength fibers using a directional coupler method," Opt. Express **17**, 8012–8028 (2009).]

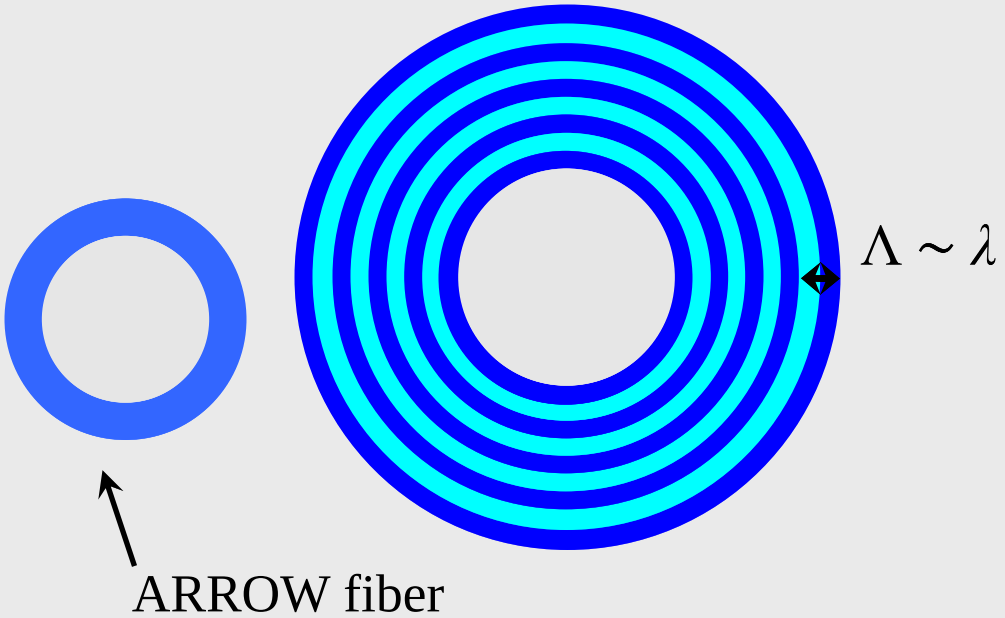
Plastic fibers for terahertz waves

SOLID CORE



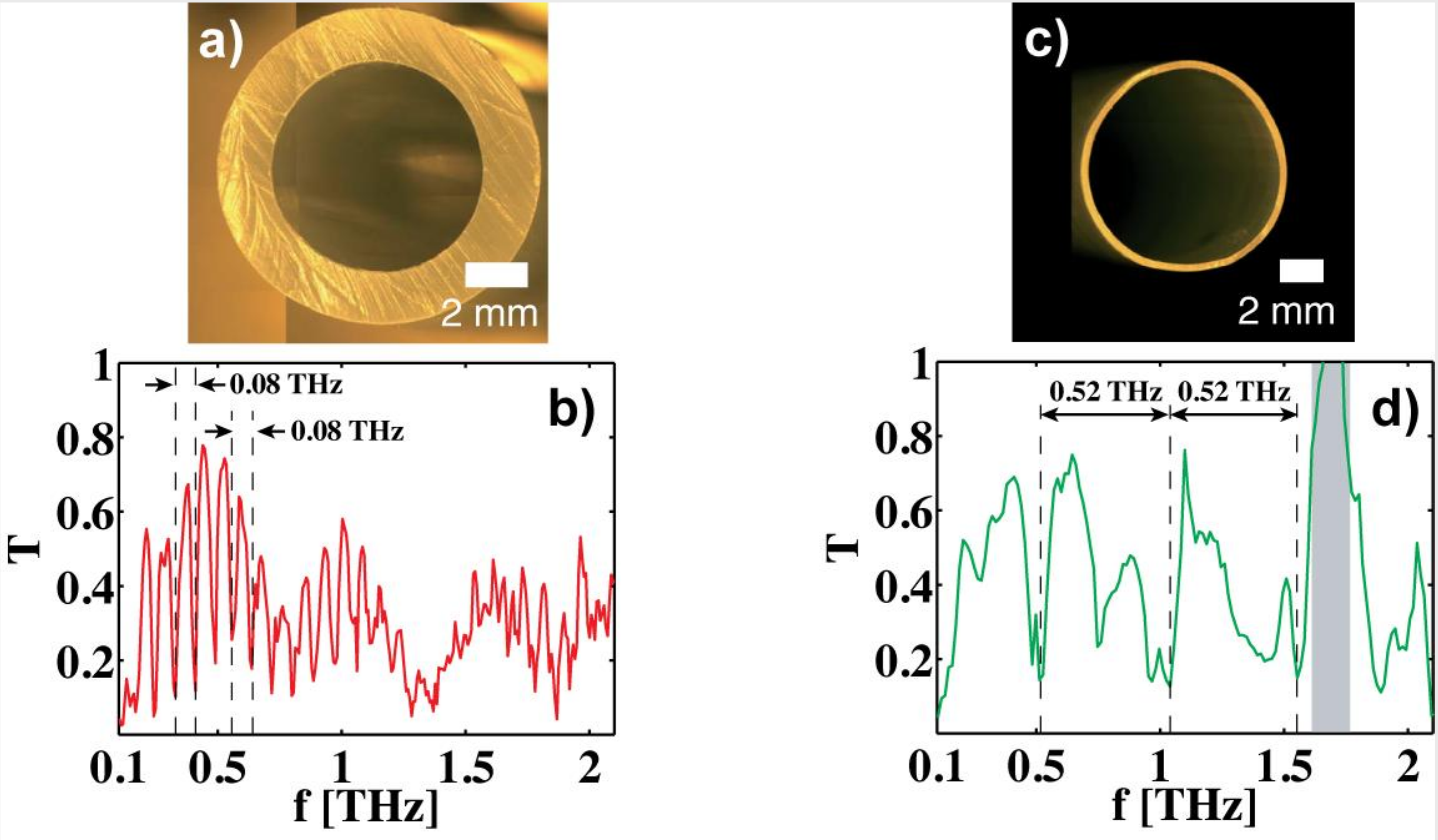
HOLLOW CORE FIBERS

$$\alpha \sim \frac{1}{r_{core}^3 \nu^2}$$



$$f_m = \frac{c \cdot m}{2t\sqrt{n_{clad}^2 - n_{core}^2}}, \quad m = 1, 2, 3, \ldots$$

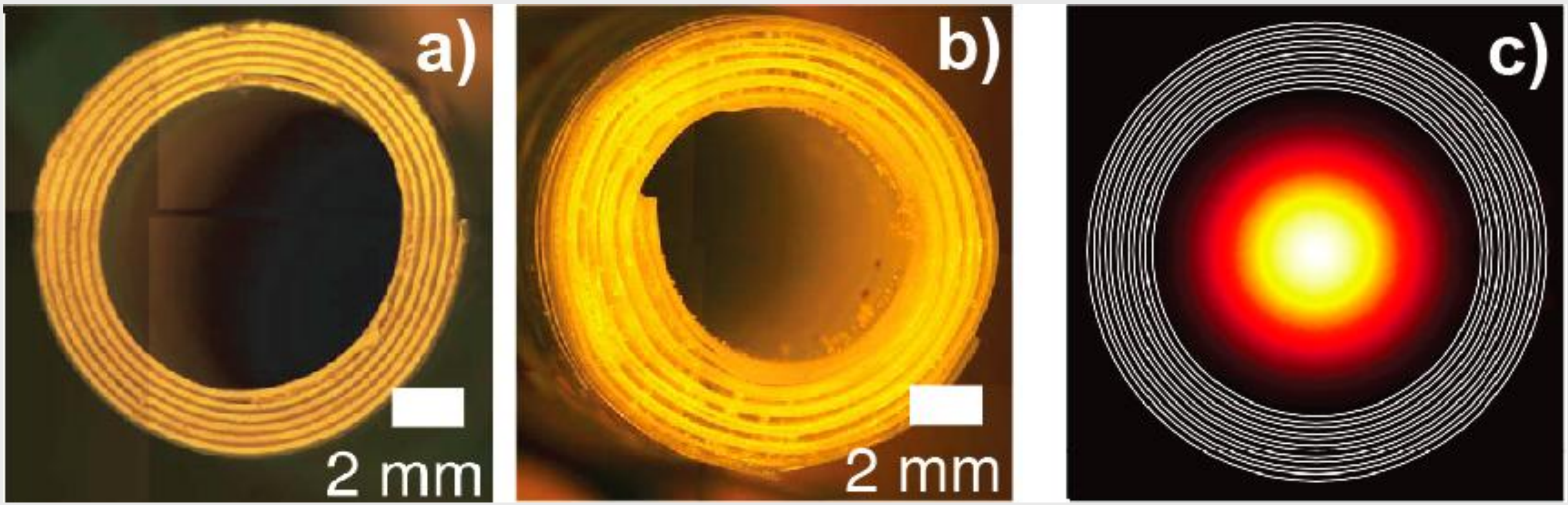
ARROW-based transmission in plastic capillaries



[A. Dupuis, K. Stoeffler, B. Ung, C. Dubois, and M. Skorobogatiy, "Transmission measurements of hollow-core THz Bragg fibers," J. Opt. Soc. Am. B **28**, 896 (2011)]

Plastic Bragg fibers

PE / TiO_2 doped layers | PE / air layers (with PMMA spacers) | HE_{11} fundamental mode

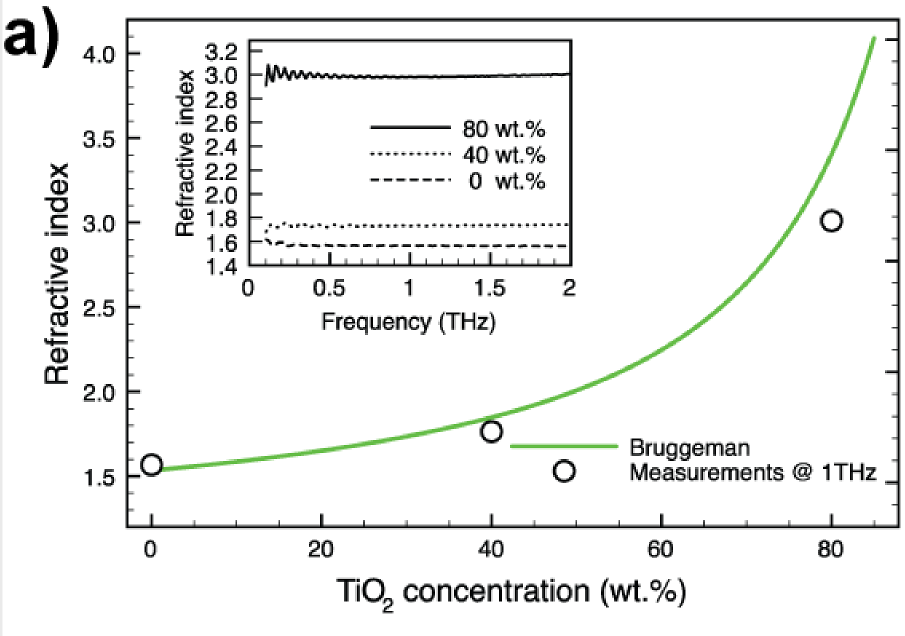


[A. Dupuis, K. Stoeffler, B. Ung, C. Dubois, and M. Skorobogatiy, *J. Opt. Soc. Am. B,* **28** (2011)]

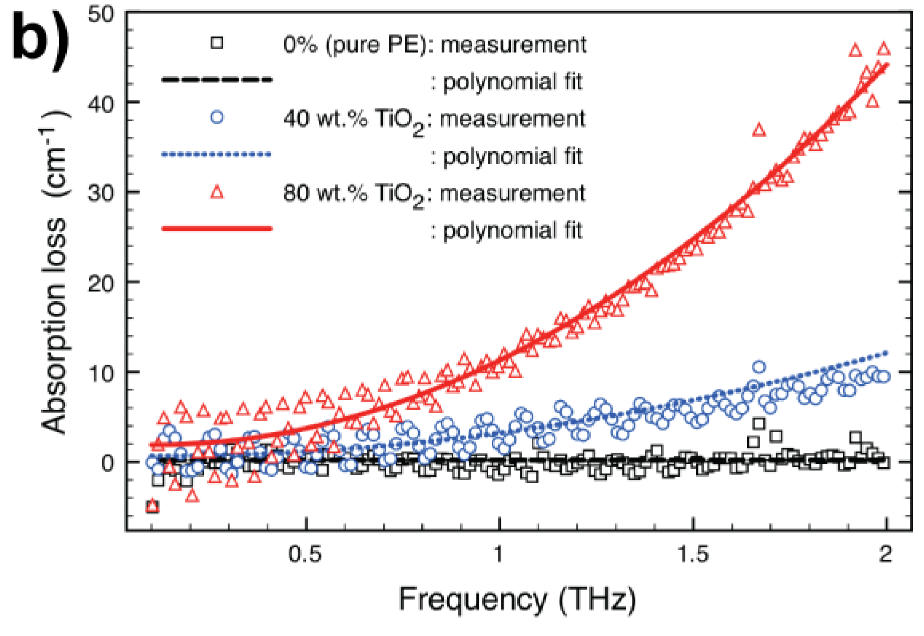
Optical properties of the polyethylene (PE) / TiO_2 compounds

TiO_2 -doped PE optical properties

Refractive index



Absorption coefficient



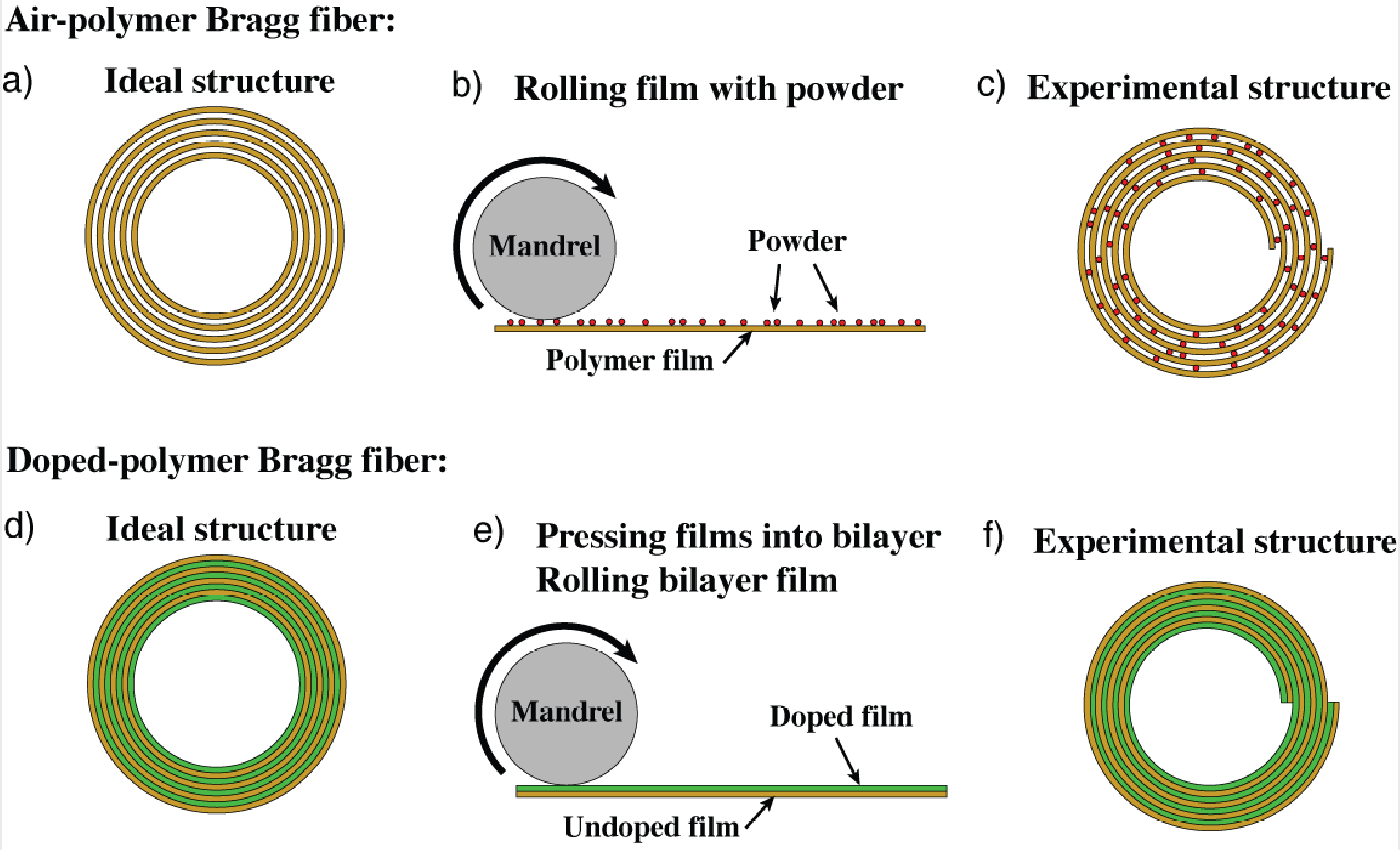
Bruggeman:

$$1 - f_v = \frac{\varepsilon_p - \varepsilon_m}{\varepsilon_p - \varepsilon_h}\sqrt{\frac{\varepsilon_h}{\varepsilon_m}}$$

f_v : volume fraction of dopants
ε_p : permittivity of particles
ε_h : permittivity of host
ε_m : permittivity of mixture

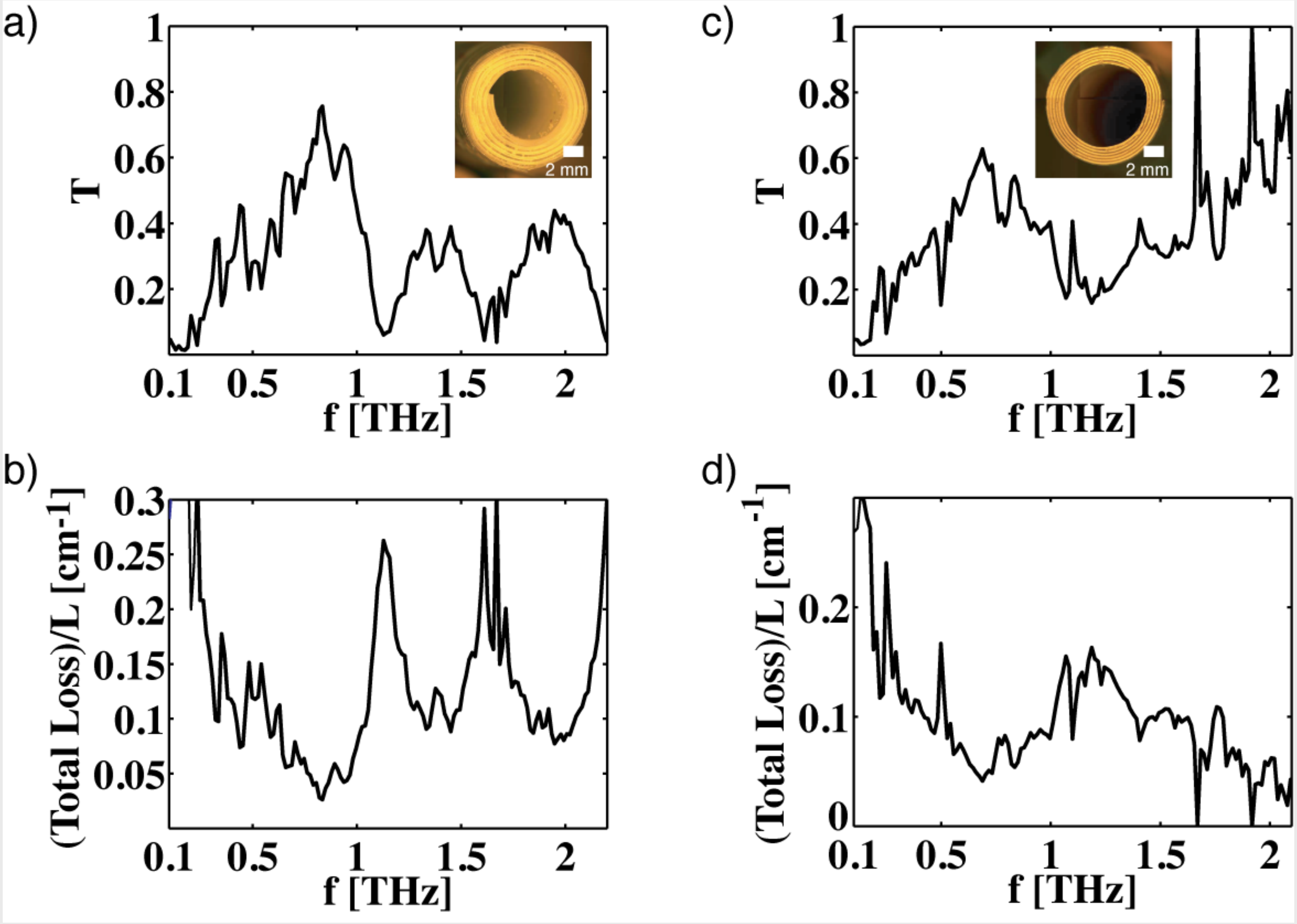
[B. Ung, A. Dupuis, K. Stoeffler, C. Dubois, and M. Skorobogatiy, *J. Opt. Soc. Am. B,* **28** (2011)]

Fabrication of plastic Bragg fibers



[A. Dupuis, K. Stoeffler, B. Ung, C. Dubois, and M. Skorobogatiy, *J. Opt. Soc. Am. B,* **28** (2011)]

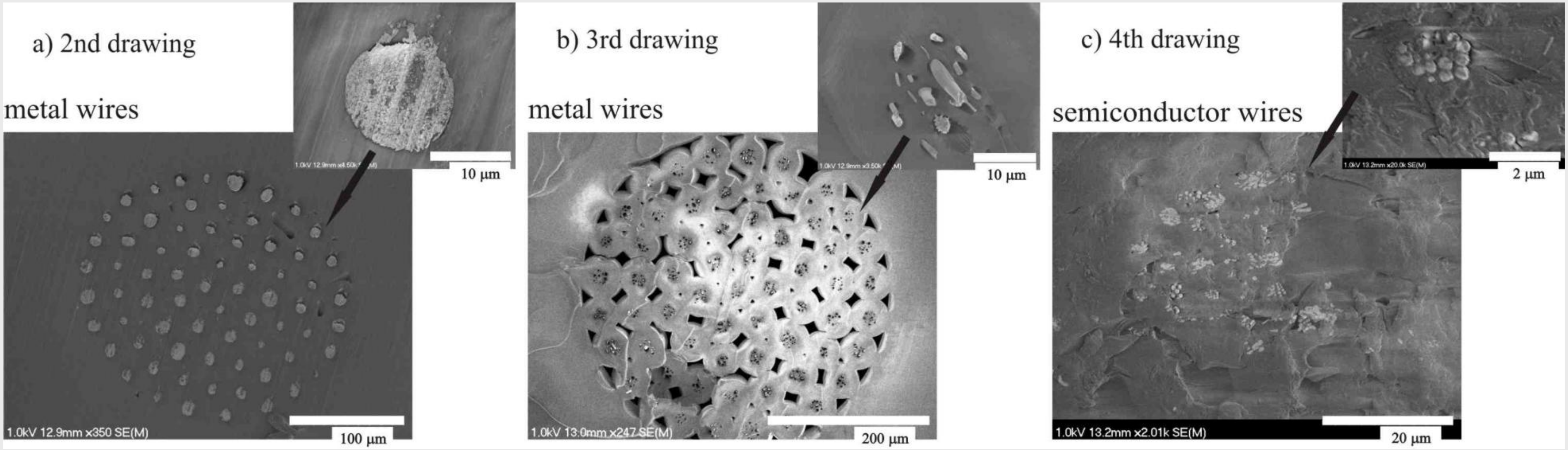
Transmission of plastic Bragg fibers



[A. Dupuis, K. Stoeffler, B. Ung, C. Dubois, and M. Skorobogatiy, *J. Opt. Soc. Am. B,* **28** (2011)]

Composite terahertz materials: fabrication

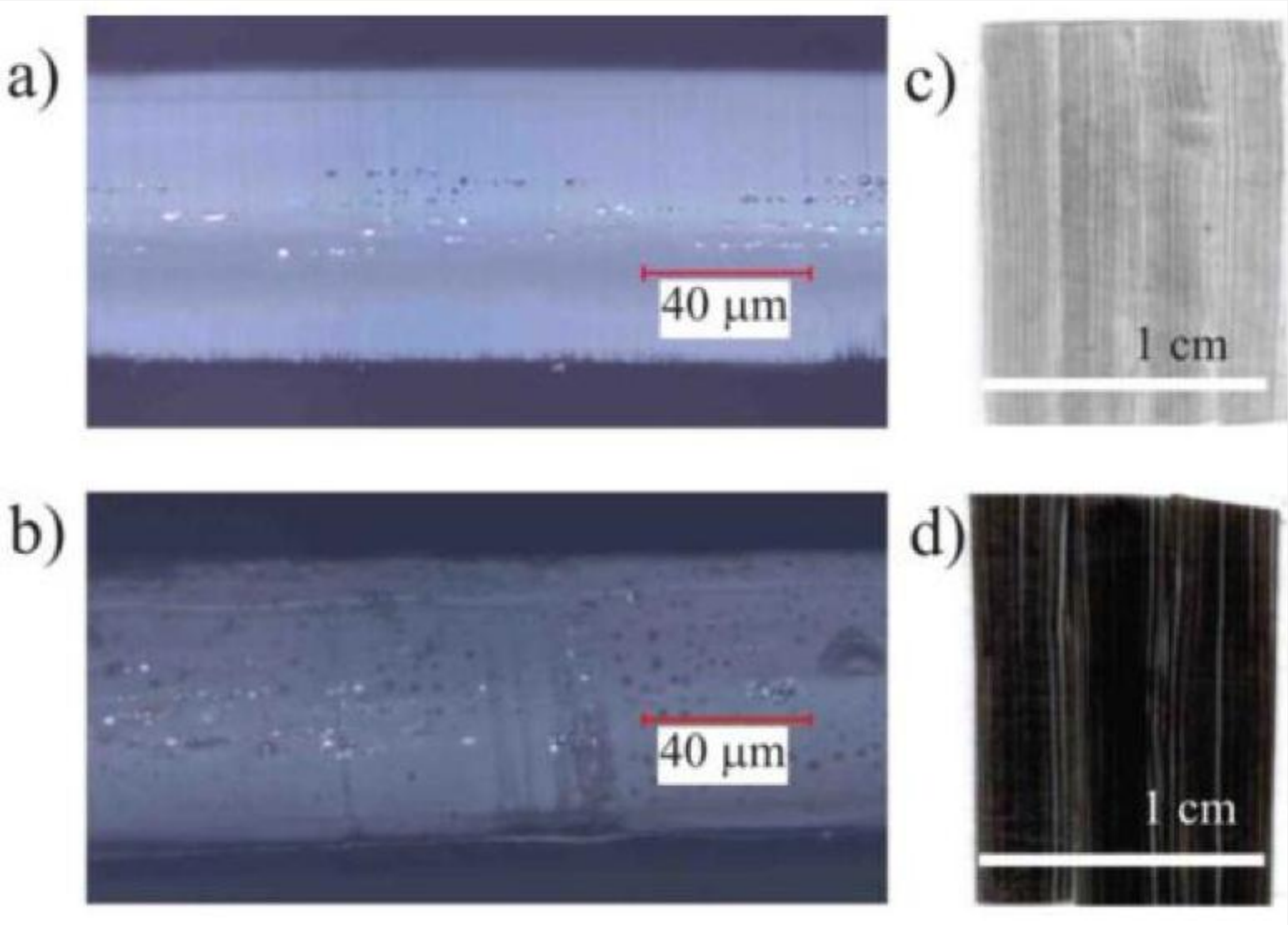
Consecutive stack-and-draw technique towards fabrication of micro(-nano) wire arrays



[A. Mazhorova, J. Gu, A. Dupuis, M. Peccianti, O. Tsuneyuki, R. Morandotti, H. Minamide, M. Tang, Y. Wang, H. Ito, and M. Skorobogatiy, *Opt. Express,* **18** (2010)]

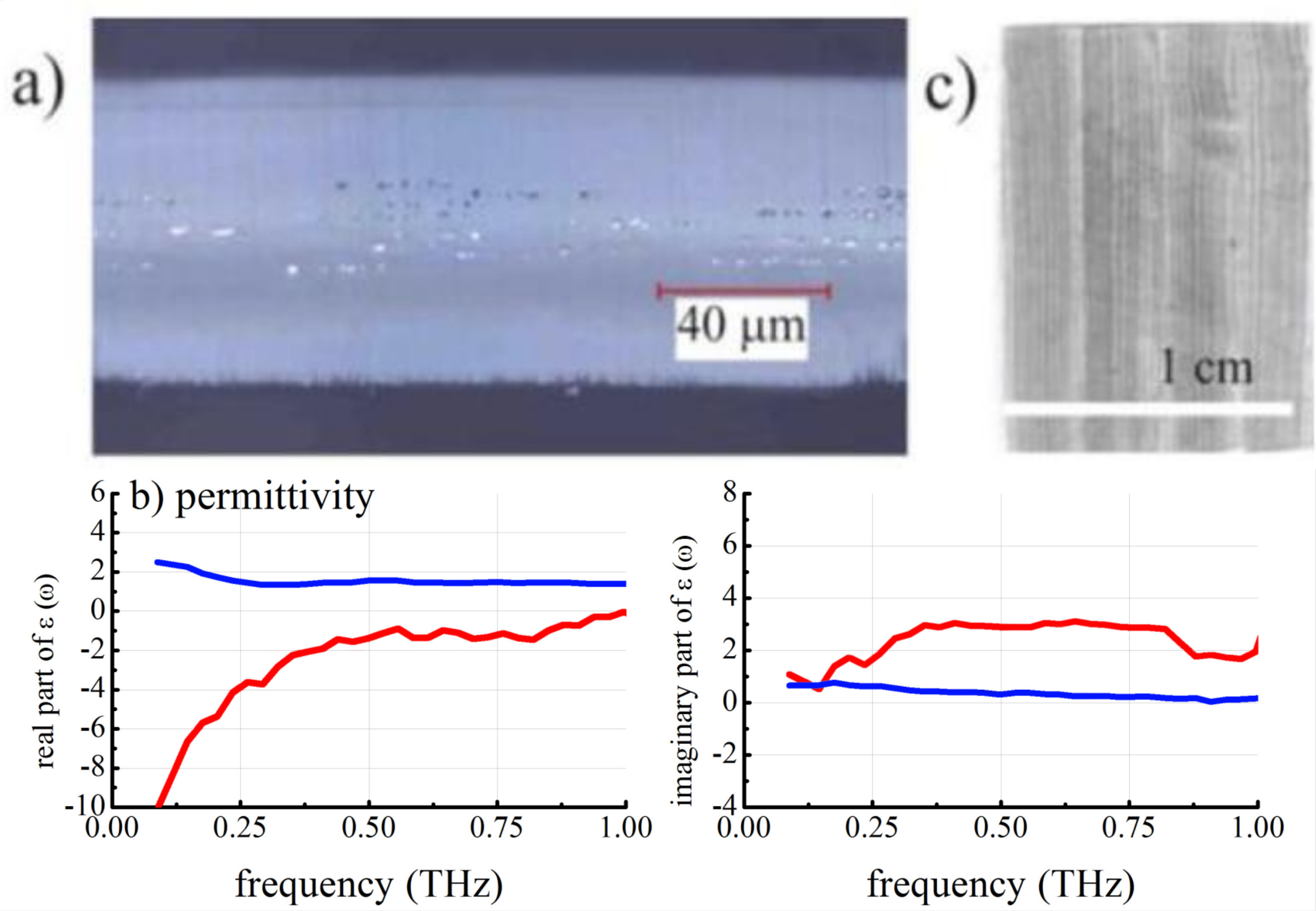
Composite terahertz materials: fabrication

Planar metamaterial film fabrication by pressing fibers containign wire arrays



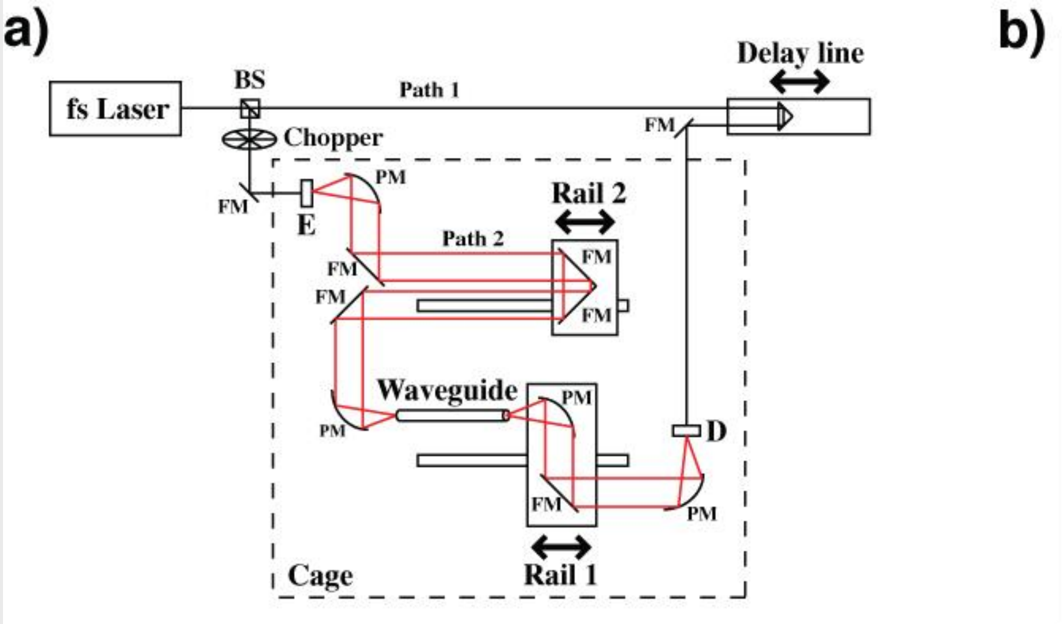
[A. Mazhorova, J. Gu, A. Dupuis, M. Peccianti, O. Tsuneyuki, R. Morandotti, H. Minamide, M. Tang, Y. Wang, H. Ito, and M. Skorobogatiy, *Opt. Express,* **18** (2010)]

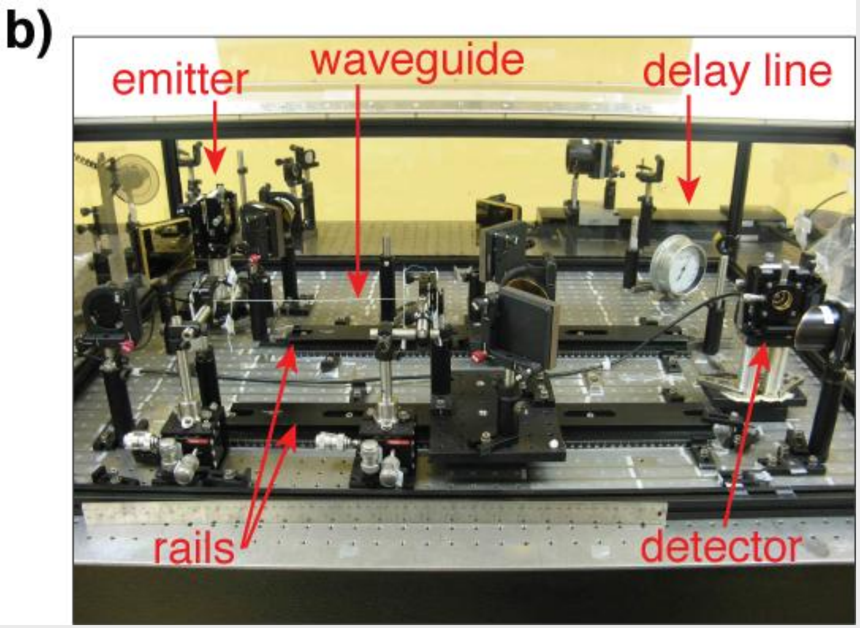
Composite terahertz materials: optical properties



[A. Mazhorova, J. Gu, A. Dupuis, M. Peccianti, O. Tsuneyuki, R. Morandotti, H. Minamide, M. Tang, Y. Wang, H. Ito, and M. Skorobogatiy, *Opt. Express,* **18** (2010)]

Reconfigurable THz-TDS setup for waveguide measurements





[A. Dupuis, A. Mazhorova, F. Désévédavy, M. Rozé and M. Skorobogatiy, *Opt. Express*, **18** (2010)]

Conclusions (subwavelength fibers)

- To counteract material bulk absorption losses, the most effective approach is to minimize the fraction of power guided in lossy material regions: subwavelength fibers OR hollow-core fibers
- Compared to a solid core fiber of the same diameter, porous subwavelength fiber enables higher fraction of light to be guided in the low-loss air region. Transmission window of a porous fiber is, therefore, broader and shifted to higher frequencies.
- Compared to a solid core fiber of the same diameter, porous subwavelength fiber show lower group velocity dispersion, while its bending loss is superior to a solid core fiber due to high confinement of light in the porous air core.
- Packaging of fibers is crucial for practical applications:

-protective tubing shields core-guided mode from interacting with the environment

-allows to forgo a purging cage by filling directly fiber cladding with a dry gas

-enables direct and convenient handling of fibers during experiments

Conclusions (ARROW, Bragg fibers, new THz materials)

- Low-loss THz guiding possible in ARROW fibers. Thinner capillaries = wider trasmission windows.
- Bragg fibers with thicker cladding confers greater mechanical stability compared to the thin-walled ARROW fibers, provides stronger modal confinement, and consequently, lower bending losses and reduced sensitivity to the environment.
- Possible to obtain very wide bandgaps with Bragg fibers provided that a high-refractive-index contrast is present in the bilayers of the periodic reflector.
- Composite THz materials based on polymers doped with high-index particles OR polymers with embedded metallic/semiconductor wires.
- Metallic micro/nano-wire media enables design of artificial materials with tunable refractive index and remarkable polarization properties.

ÉCOLE POLYTECHNIQUE MONTRÉAL

PolyPhotonique

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ICIP CIPI

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- Canada Research Chair Foundation
- Canadian Institute for Photonics Innovations