Plastic fibers for terahertz wave guiding

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Standard solid core TIR fiber in THz

Terahertz: \( \nu = 0.1-10 \text{ THz} \iff \lambda = 3000-30 \text{ \( \mu \)m} \)

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

\[ n_{\text{PE}} \approx 1.514 \]

\[ \alpha = 0.46 f^2 - 0.10 f + 0.13 \ \text{[cm}^{-1}] \]

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

Lowering absorption loss in TIR fibers

Holes filled with dry gas

Lower loss dielectrics by chemistry or composite materials
Lowering absorption loss in fibers.
Hollow core guidance.
Plastic fibers for terahertz waves studied in our group

**SOLID CORE**

- $d < \lambda$
- Subwavelength core
- $\Lambda \sim \lambda$

**HOLLOW CORE**

- $\alpha \sim \frac{1}{r_{core}^3 V^2}$
- $\Lambda \sim \lambda$
- ARROW fiber
- PBG fiber

**POROUS CORE**

- $\Lambda << \lambda$
Subwavelength dielectric fibers

solid core

\[ d < \lambda \]

\[ d = 120 \, \mu m \]

\[ f_\alpha = 28 \% \]

porous core

\[ \Lambda \ll \lambda \]

\[ d < \lambda \]

\[ d = 120 \, \mu m \]

\[ f_\alpha = 12 \% \]

Lower loss dielectrics by composite materials

Guidance by total internal reflection

Transmission and losses of porous fibers

Fabrication of porous fibers

a) Sacrificial polymer technique
Solidification of preform

PE/PMMA preform

Drawing into fiber
Dissolution of sacrificial polymer

Gray: PTFE
Orange: PE
Green: PMMA

b) Microstructured molding technique
Molding of preform

Mold + polymer
Molded preform
Preform

Drawing under pressure to inflate fiber holes

Packaging of subwavelength fibers: encapsulation within a protective tube

solid core

$\text{OD} = 5.1 \text{ mm}$

$d_{\text{core}} \sim 150 \mu\text{m}$

porous core

$\text{OD} \sim 3.0 \text{ mm}$

$d_{\text{core}} \sim 900 \mu\text{m}$

THz near-field imaging setup

[Image of THz near-field imaging setup diagram]

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

0.16 THz

0.30 THz

0.48 THz

Experiment

Simulation

Suspended fibers: transmission spectrum and propagation losses

\[ \text{min loss } \leq 0.02 \text{ cm}^{-1} \]

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

Fiber-scanning THz imaging technique.

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

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

Plastic fibers for terahertz waves

SOLID CORE

porous core

Λ ≪ λ

d < λ

Λ ∼ λ

HOLLOW CORE FIBERS

ARROW fiber

Λ ∼ λ

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

\[ \alpha \sim \frac{1}{r_{core}^3 V^2} \]
ARROW-based transmission in plastic capillaries

Plastic Bragg fibers

PE / TiO$_2$ doped layers

PE / air layers (with PMMA spacers)

HE$_{11}$ fundamental mode

Optical properties of the polyethylene (PE) / TiO$_2$ compounds

TiO$_2$ -doped PE optical properties

![Graph showing refractive index and absorption coefficient vs. TiO$_2$ concentration and frequency](image)

**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
- $\varepsilon_p$ : permittivity of particles
- $\varepsilon_h$ : permittivity of host
- $\varepsilon_m$ : permittivity of mixture

Fabrication of plastic Bragg fibers

**Air-polymer Bragg fiber:**

a) **Ideal structure**

b) **Rolling film with powder**

 c) **Experimental structure**

**Doped-polymer Bragg fiber:**

d) **Ideal structure**

e) **Pressing films into bilayer**

f) **Experimental structure**

Rolling bilayer film

Transmission of plastic Bragg fibers

Composite terahertz materials: fabrication

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

Planar metamaterial film fabrication by pressing fibers containing wire arrays

Composite terahertz materials: optical properties

Reconfigurable THz-TDS setup for waveguide measurements

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
• Low-loss THz guiding possible in ARROW fibers. Thinner capillaries = wider transmission 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.
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