Spectroscopy of ITO coatings in optical and microwave ranges

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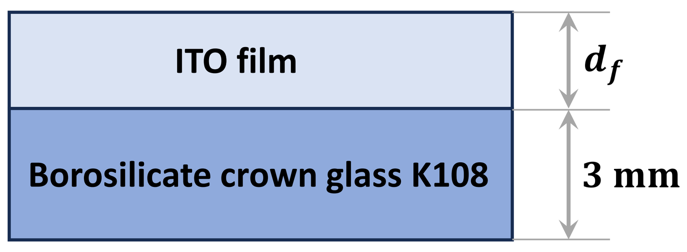
Introduction

Among the numerous applications of indium tin oxide (ITO) films in electronics, optics and optoelectronics, the use of ITO coatings for shielding electromagnetic interference in the microwave spectral range occupies a special place [1, 2]. Conductive ITO coatings deposited on a dielectric substrate are widely used as protective windows in optoelectronic devices operating in visible and near-IR ranges. An important task is the development of contactless methods for determining the ITO film parameters. One such method was recently proposed in [3].

The goal of the work: to develop a non-destructive optical method for determining the ITO film parameters and to study the microwave shielding effectiveness of the ITO coatings.

Samples: ITO films on a glass substrate

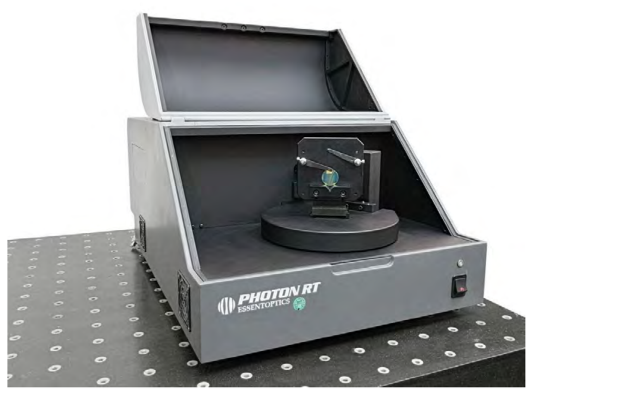


Datasheet of the samples

Sample #	Film thickness d_f, nm	Sheet resistivity ρ_S, Ohm/□
1	76	30
2	109	25
3	119	20
4	150	15
5	167	10
6	457	4

Experiments in optical range

Experimental equipment

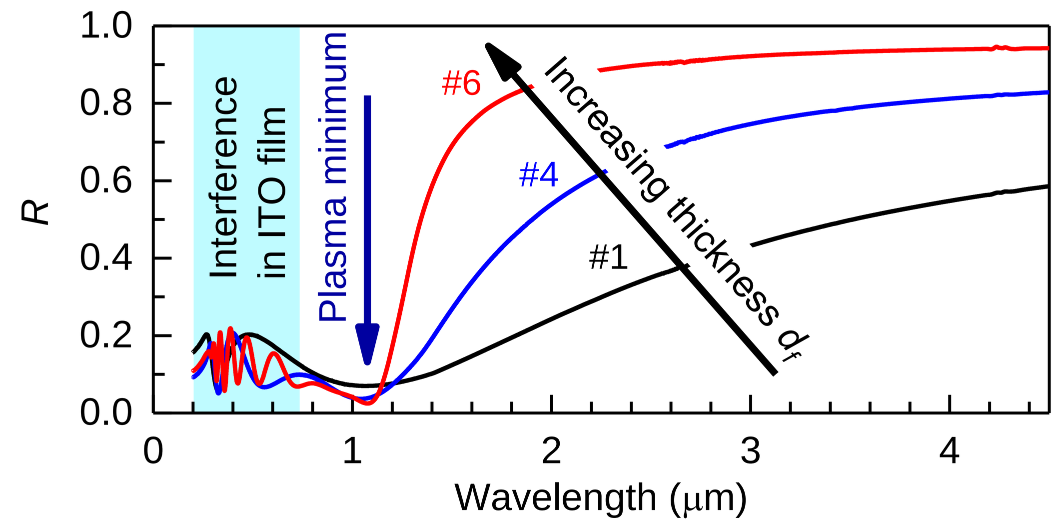


Photon RT diffraction grating spectrophotometer (EssentOptics)
λ: 0.185 – 1.65 μm

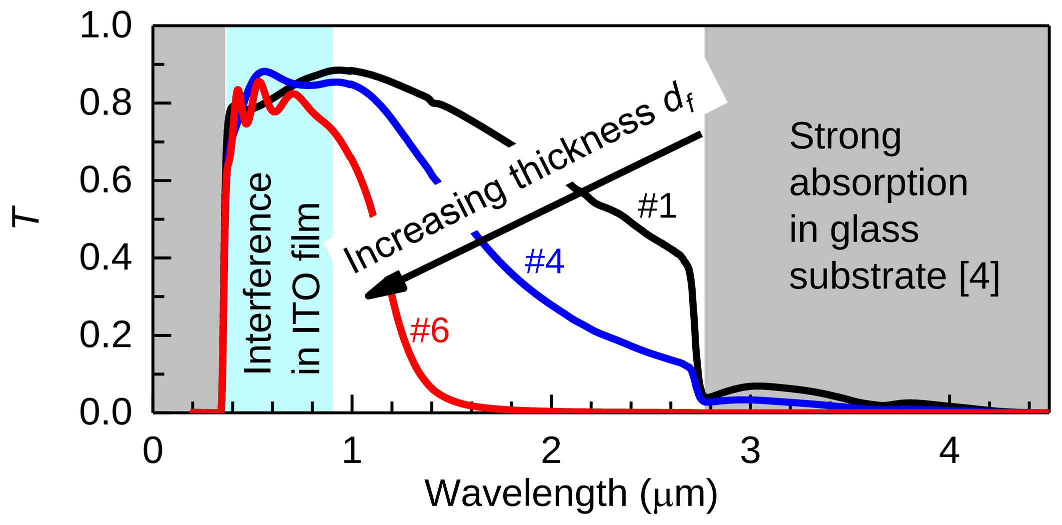
Vertex 70 Fourier-transform infrared spectrometer (Bruker)
λ: 0.667 – 335 μm

Experimental results

Reflectivity spectra of ITO films on glass substrate



Transmission spectra of ITO films on glass substrate



Non-destructive method for determining ITO film parameters

Dielectric permittivity

$$\varepsilon(\omega) = \varepsilon_\infty\left(1 - \frac{\omega_p}{\omega\left(\omega + \frac{i}{\tau}\right)}\right)$$ Drude model

$$\omega_p = \sqrt{\frac{4\pi N_e e^2}{\varepsilon_\infty m_e}}$$ Plasma frequency

$$\tau = \frac{m_e \mu}{e}$$ Relaxation time

$$m_e = 0.35 m_0$$ Effective mass

Fresnel equations:

$$\varepsilon(\omega) = \tilde{n}_i = (n + ik)^2$$

$$n(\omega) = Re\sqrt{\varepsilon(\omega)}$$ refractive index

$$k(\omega) = Im\sqrt{\varepsilon(\omega)}$$ extinction coefficient

Transverse matrix method (TMM)

Transfer matrix for the *i*-th layer (*i* = 1, 2) :

$$\mathbf{P}_1 = \begin{pmatrix} e^{-i\phi_1} & 0 \\ 0 & e^{i\phi_1} \end{pmatrix};\ \mathbf{P}_2(\delta) = \begin{pmatrix} e^{-i(\phi_2+\delta/2)} & 0 \\ 0 & e^{i(\phi_2+\delta/2)} \end{pmatrix}$$

$$\phi_i = \frac{\omega}{c}\tilde{n}_i d_i$$ Incoherent layer [5]

Transfer matrix for *i*/(*i*+1) interface:

$$\mathbf{D}_{i/(i+1)} = \frac{1}{t_{i/(i+1)}}\begin{pmatrix} 1 & r_{i/(i+1)} \\ r_{i/(i+1)} & 1 \end{pmatrix}$$

$$t_{i/(i+1)} = \frac{2\tilde{n}_i}{\tilde{n}_i + \tilde{n}_{i+1}};\ r_{i/(i+1)} = \frac{\tilde{n}_i - \tilde{n}_{i+1}}{\tilde{n}_i + \tilde{n}_{i+1}}$$

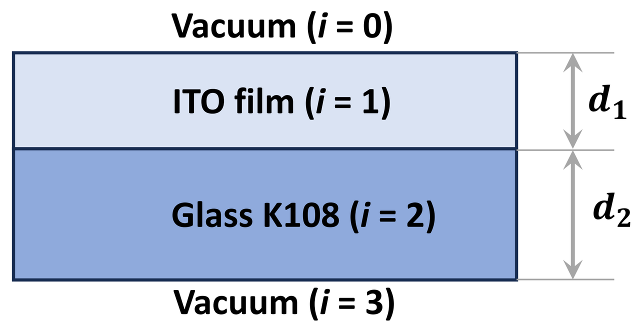
The transfer matrix for the entire structure:

$$\mathbf{M}(\delta) = \mathbf{D}_{0/1}\mathbf{P}_1\mathbf{D}_{1/2}\mathbf{P}_2{}'(\delta)\ \mathbf{D}_{2/3}$$

Reflectivity (*R*) and transmittance (*T*) of the structure:

$$R = \frac{1}{2\pi}\int_{-\pi}^{\pi}\left|\frac{1}{\mathbf{M}_{11}(\delta)}\right|^2 d\delta$$

$$T = \frac{1}{2\pi}\int_{-\pi}^{\pi}\left|\frac{\mathbf{M}_{21}(\delta)}{\mathbf{M}_{11}(\delta)}\right|^2 d\delta$$



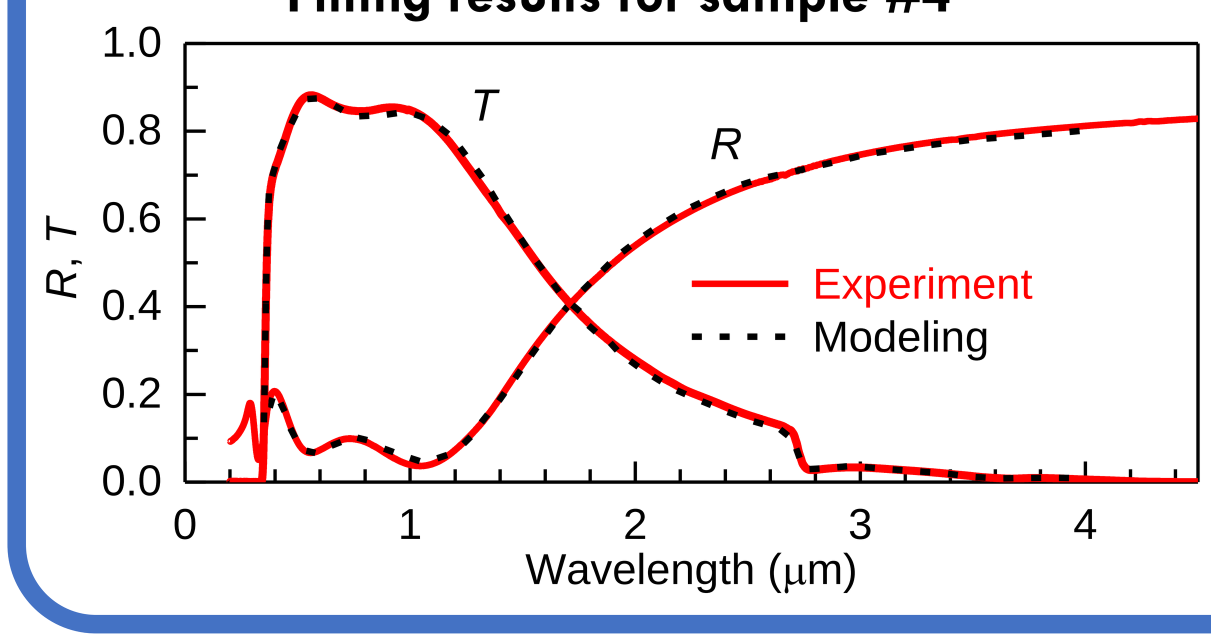
Goal function

$$S = \frac{1}{k}\sum_{j=1}^{k}\frac{1}{n}\sum_{i=1}^{n}\left(\Delta_{ji}\right)^2$$

Fitting parameters

Thickness of the ITO films $d_f \equiv d_1$
Charge carrier concentration N_e
Charge carrier mobility μ

Fitting results for sample #4



Best fit parameters: High accuracy!

Sample #	d_f, nm	N_e, × 10^{20} cm^{-3}	μ, $\frac{\text{cm}^2}{\text{V}\times\text{s}}$
#1	68.8 ± 0.3	8.0 ± 0.4	40 ± 2
#4	155.2 ± 0.5	8.1 ± 0.4	37 ± 1
#6	445.0 ± 2	9.9 ± 0.1	44 ± 1

A non-destructive optical method for determining the ITO film parameters d_f, N_e, μ was developed.

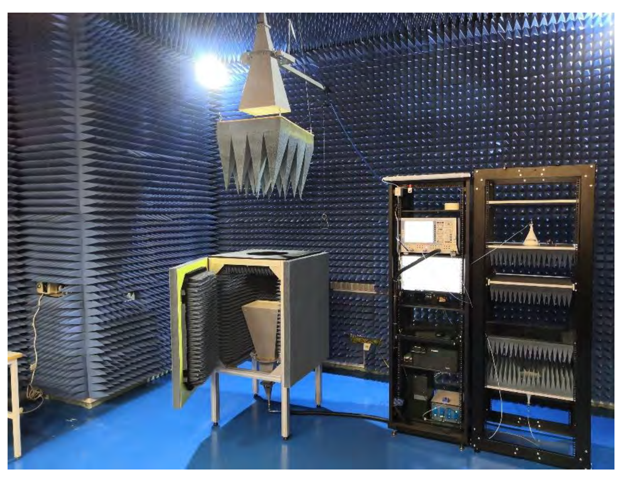
Experiments in microwave range

Experimental equipment

Free-space measurements were performed using an anechoic chamber.

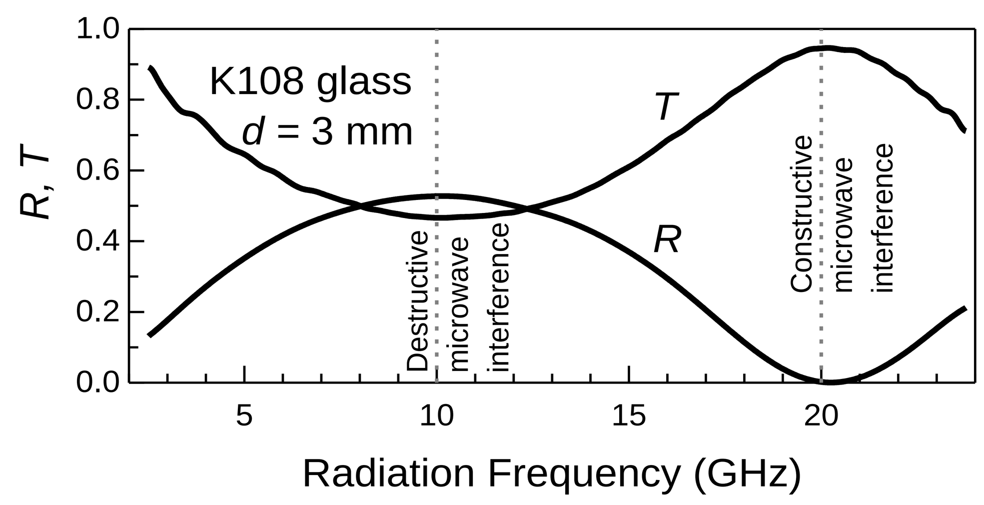
Spectral range: 2–24 GHz

Spectral resolution: 0.01 GHz

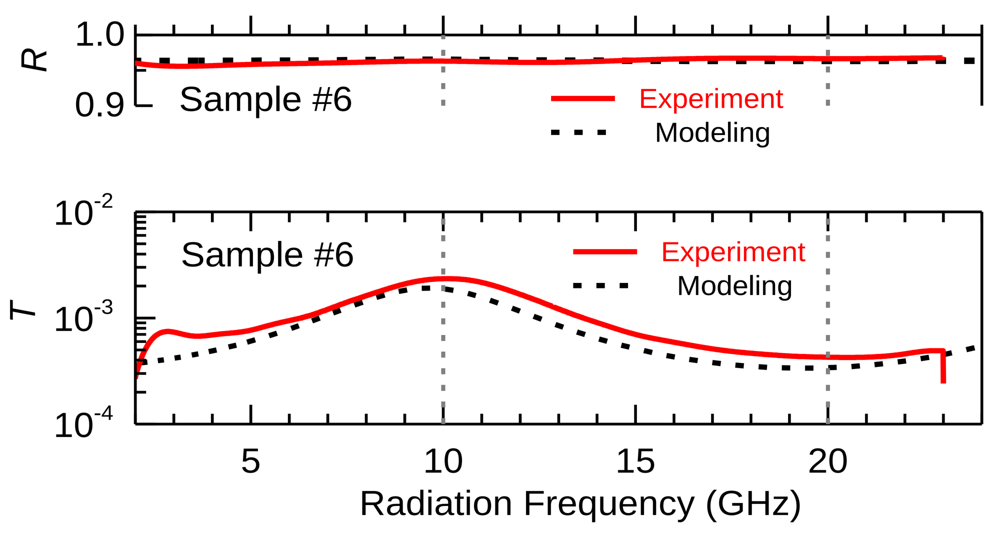


Experimental results

Spectra of the glass substrate [4]



Spectra of ITO film on the glass substrate

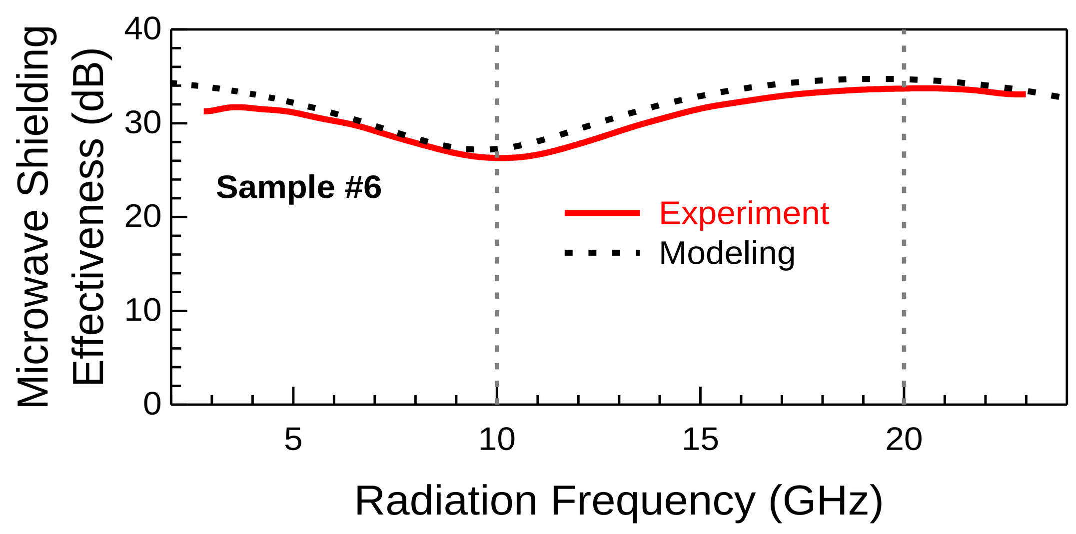


More than **99.7%** of microwave radiation **is blocked** (primarily due to **large reflectivity of the ITO film**).

The **microwave** reflectivity and transmittance spectra were simulated using the **same theoretical model** that was developed for the **optical** range.

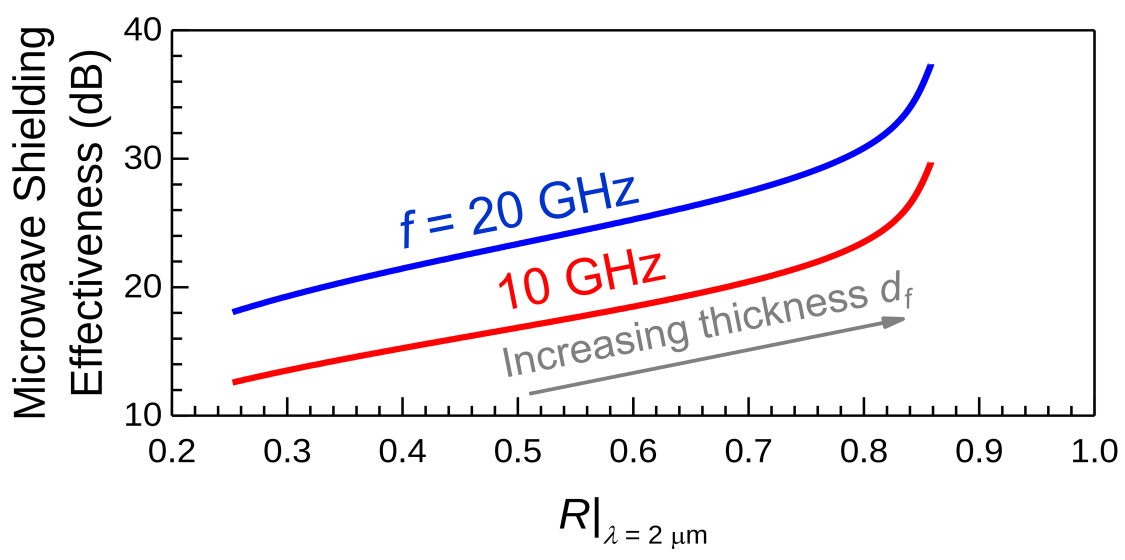
The simulated spectra are in **good agreement** with the measured ones. This is another **argument confirming the high accuracy of determining the ITO film parameters** using the method we developed.

Microwave shielding effectiveness



The **shielding effectiveness exceeds 26 dB** over the entire operating spectral range. The simulated spectra are in **good agreement** with the measured ones.

Microwave shielding effectiveness of ITO coating versus its near-IR reflectivity



Finally, we have found a correlation between the microwave shielding effectiveness of the ITO coating and its **near-infrared reflectivity**. The found dependence enables one **to predict the ITO film performance in the microwave range** at a given frequency using single reflectivity measurement in near-IR range (at a wavelength of 2 μm).

Summary

We studied experimentally and theoretically the interaction of electromagnetic radiation with the ITO coatings in optical and microwave ranges. **A non-destructive method for determining the ITO film parameters** (thickness, electron concentration and mobility) has been developed. The method is based on the analysis of reflectivity and transmittance spectra in a wavelength range of 0.2–4.5 μm. We also **examined the reflectivity and transmittance spectra of the samples in microwave range** at frequencies of 2.8–23 GHz. It has been found that **the microwave shielding efficiency exceeds 26 dB**. A relationship has been established between the microwave shielding effectiveness of the ITO coating and its near-infrared reflectivity.

References

1. J.L. Huang, et al., *Ceramics international* **27**, 363 (2001).
2. H. Wang, et al., *IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications* (Ann Arbor, USA, 16-18 July 2018), pp. 1–3.
3. D. Ananthanarayanan, et al., *Solar Energy* **209**, 424 (2020).
4. V.V. Bassarab, et al., *Journal of Optics* **25**, 065401 (2023).
5. C.C. Katsidis, *Appied Optic* **41**, 3978 (2002).