School of Electrical and Electronic Engineering
FACULTY OF ENGINEERING

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Development of Advanced Terahertz Optics using Liquid Crystals & Additive Manufacturing

Alexander Valavanis, University of Leeds

a.valavanis@leeds.ac.uk

Overview

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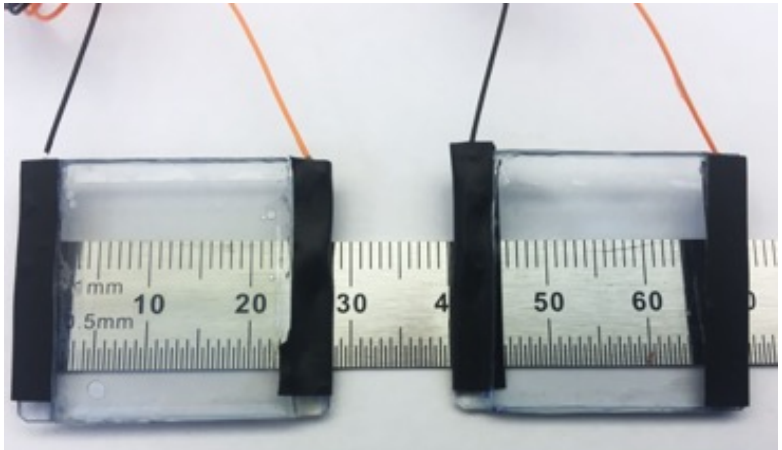
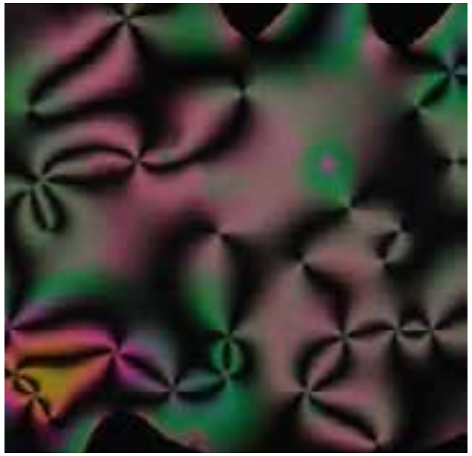
- “Supra-Terahertz” radiometry and components
- Additively manufactured optics
- Liquid-crystal adaptive optics





Terahertz (THz) radiation

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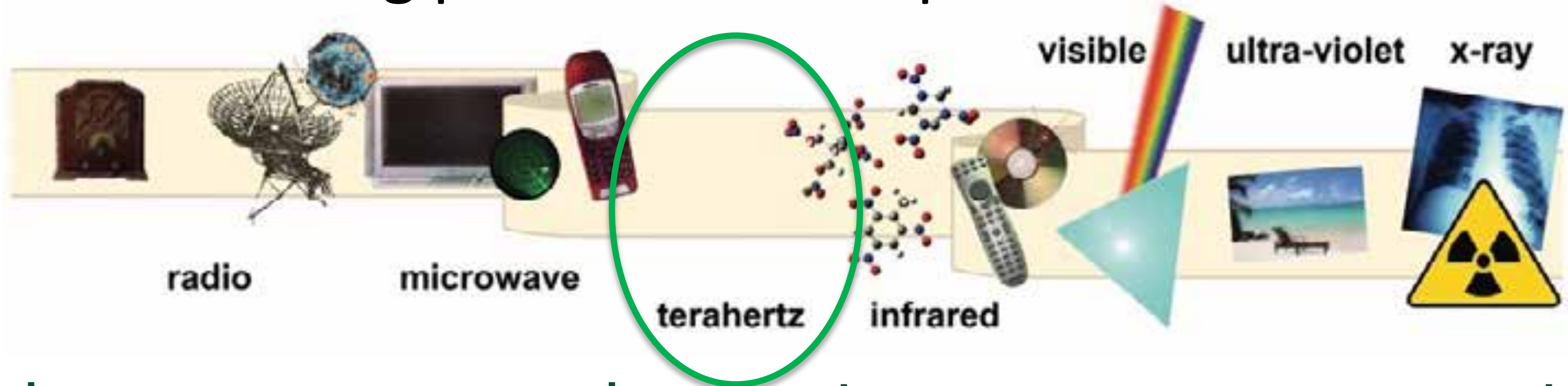
RAL Space

The meeting point between optics and electronics



Electronic oscillators

Optical sources

f = 0.3–10 THz   λ = 1–0.03 mm

k = 10–333 cm^{-1} E = 1.2–40 meV

The KEYSTONE satellite concept

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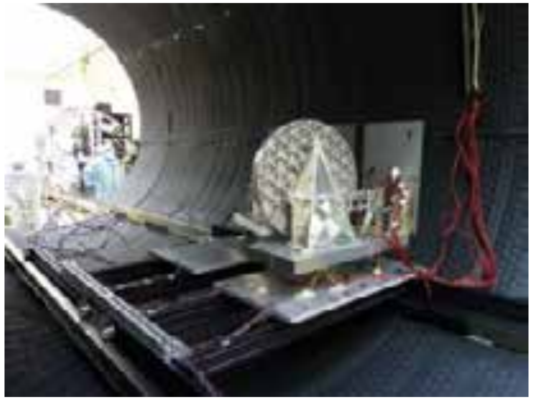
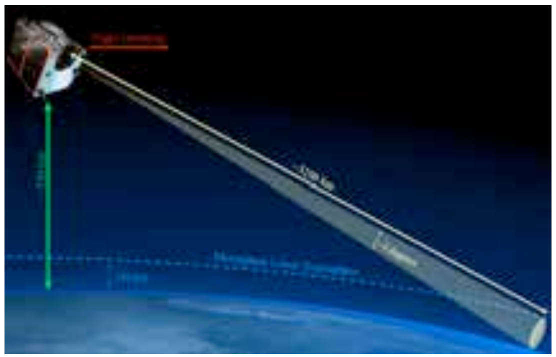
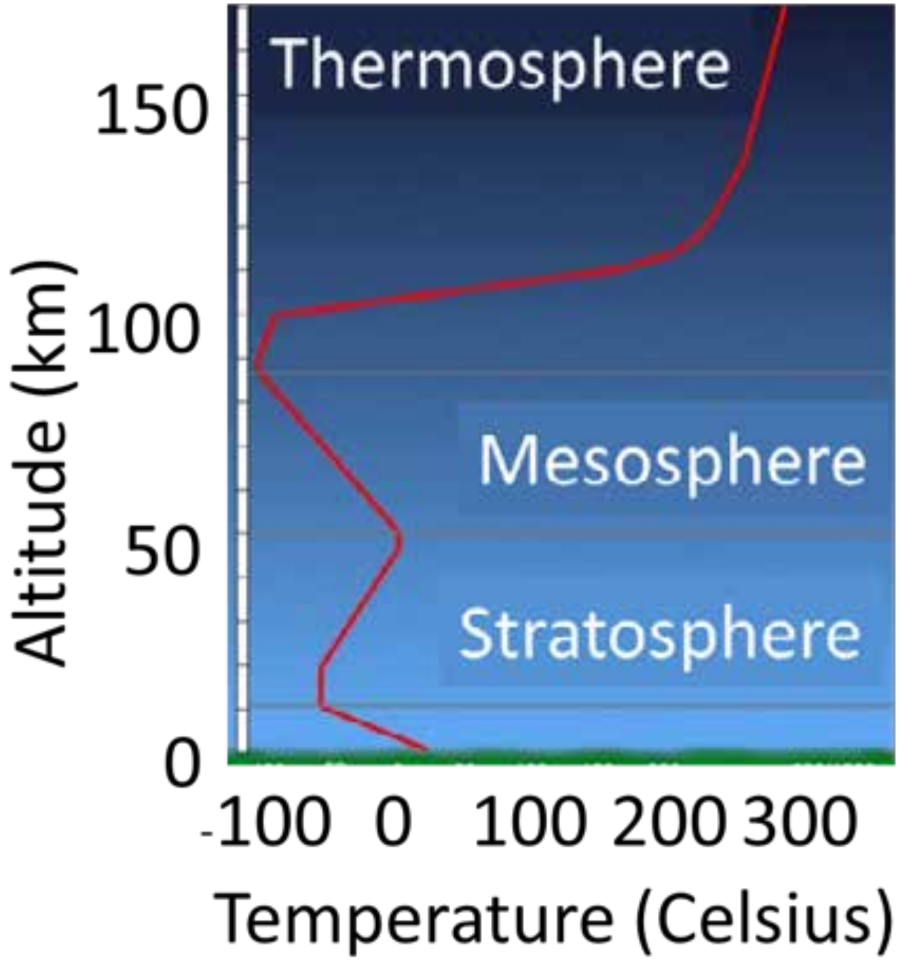
RAL Space



Designation	Band Centre	Primary Species	Secondary Species
Band 1	4.7 THz	O	O_3
Band 2	3.5 THz	OH	CO, HO_2
Band 3	1.1 THz	NO, CO	H_2O, O_3
Band 4	0.8 THz	O_2	O_3





Supra-THz optics (or lack of)

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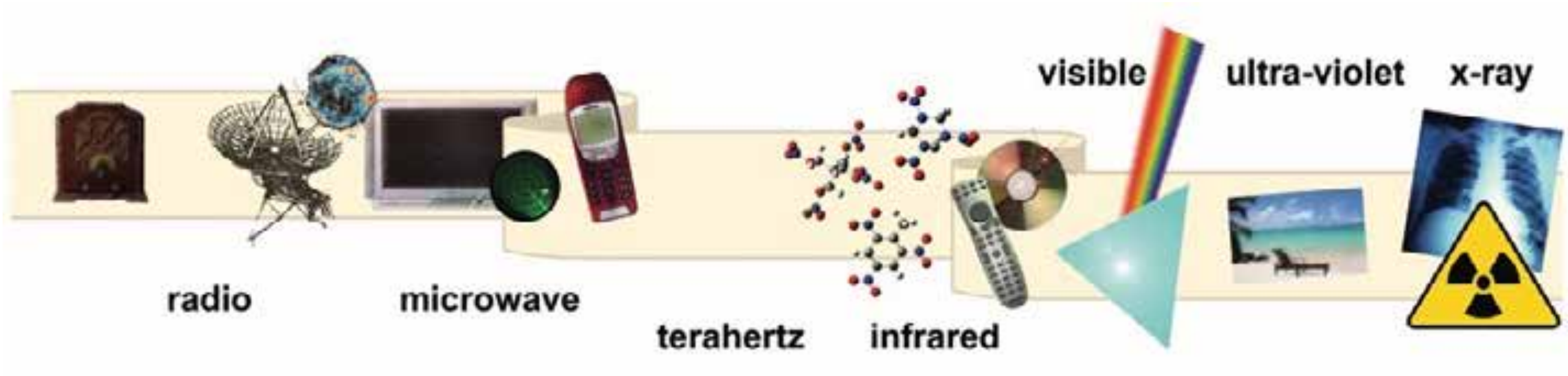

RF techniques
(reflectors, waveguides etc)

ultra-high precision needed for THz

Optical techniques
(lenses, fibres etc)

High diffraction; few materials available at THz frequencies!

New THz manufacturing techniques

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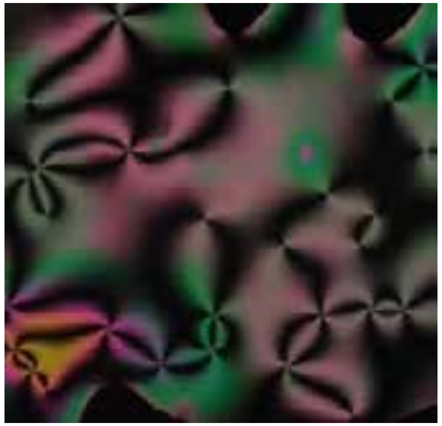
Additive manufacturing ("3D printing") of custom optical components

Liquid crystal-based devices for adaptive and controllable optics



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Additive manufacturing

Material & process selection

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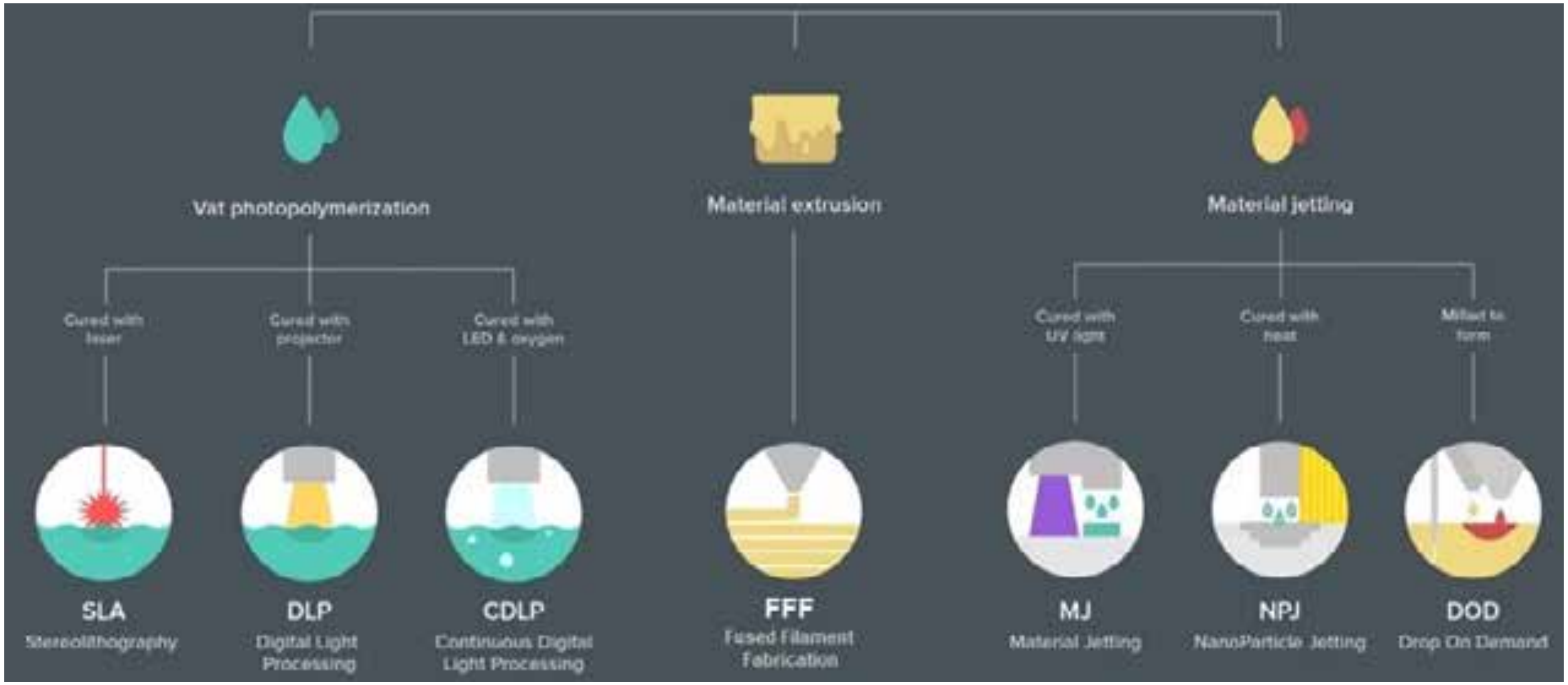
Wide range of established AM processes available

Photocurable polymers *vs* thermoplastics…



Thermoplastics

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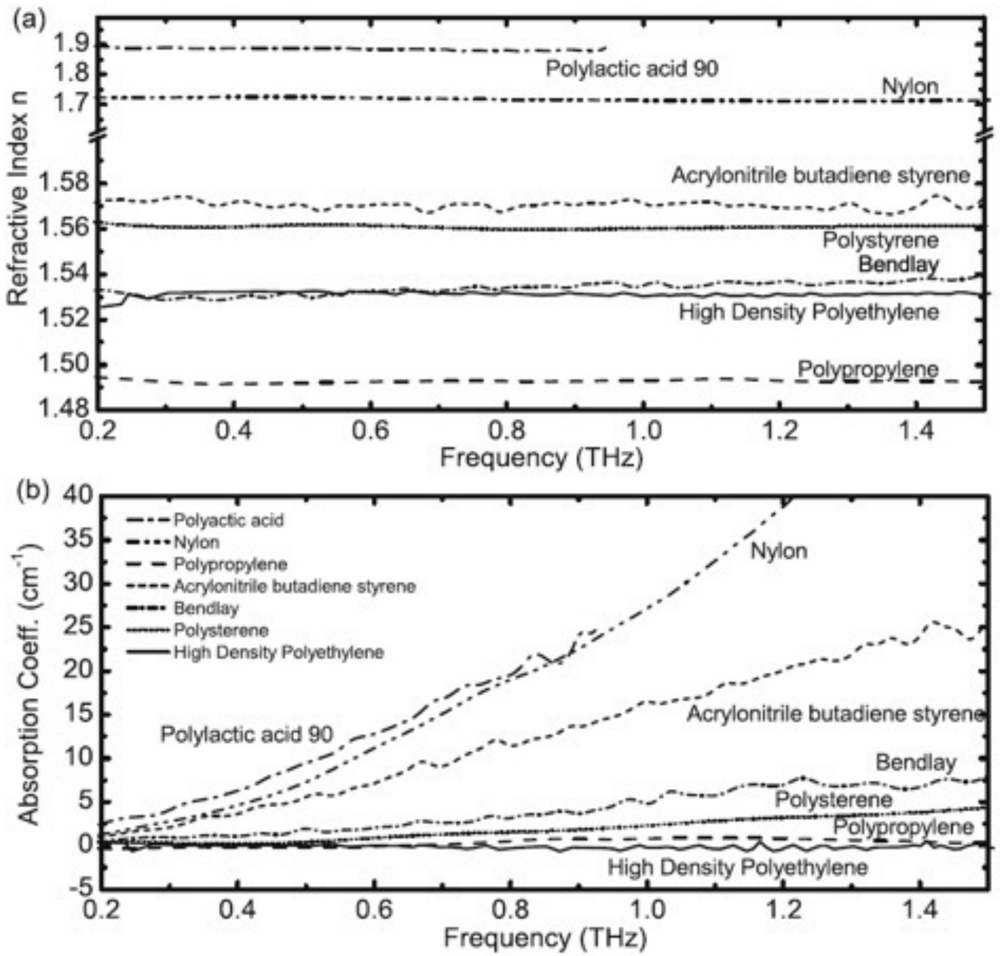
Previous studies limited to < 2 THz.

PP/PE give lowest absorption for fused-filament fabrication (FFF).

Challenging to print PP!



Busch et al., *J. IR mm & THz waves*, **35,** p. 993 (2014)

Photocurable inks

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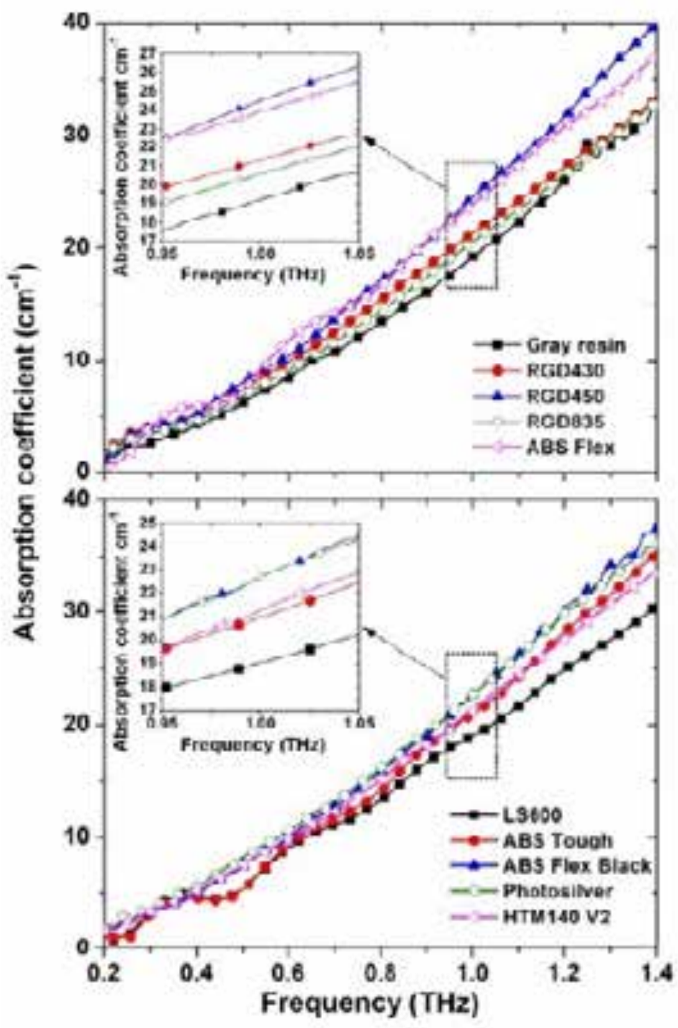
Previous studies limited to < 2 THz.

Inkjet printing/Vat polymerisation are very reliable processes.

Much higher absorption coefficients though!



Duangrit et al., *IEEE Access*, **7,** p. 12339 (2019)

Supra-THz material analysis

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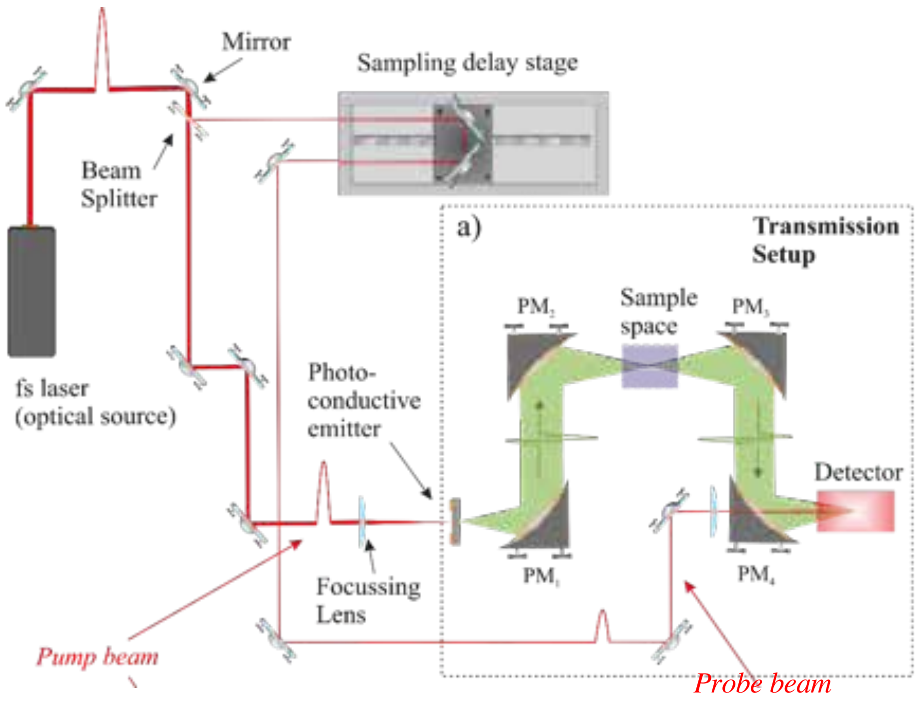
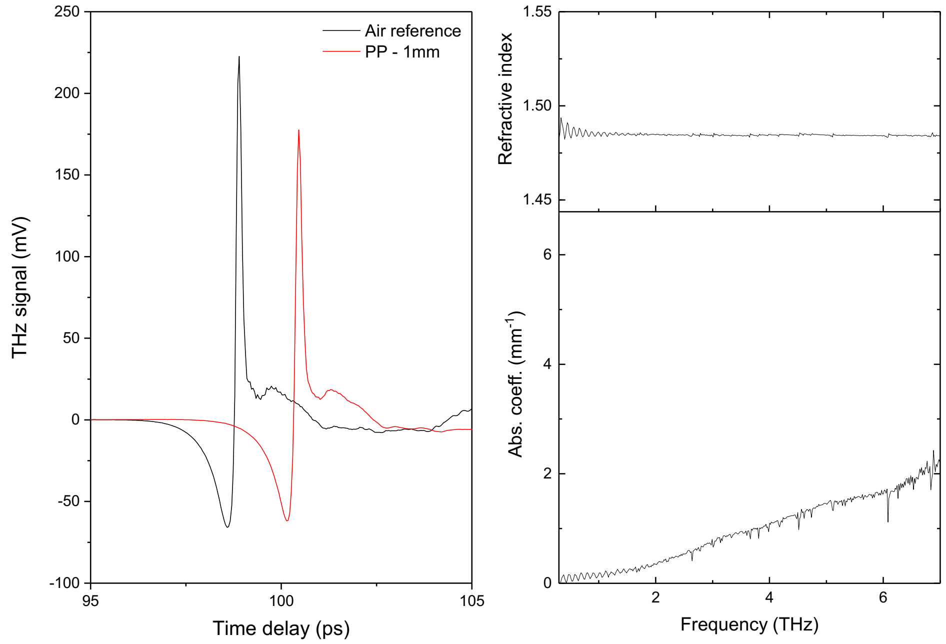
THz time-domain spectroscopy (TDS)

First AM material study over 6 THz bandwidth





Supra-THz material comparison

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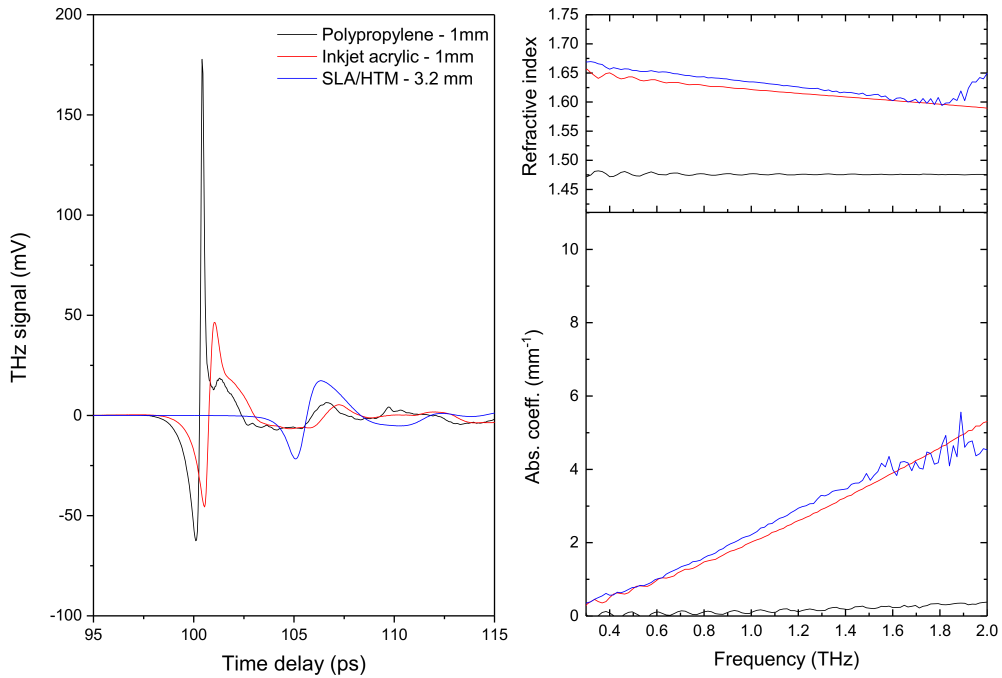
PP much lower loss than acrylics
(4.3 dB/mm vs >21 dB/mm at 3 THz)

1.49 refractive index



Process evaluation

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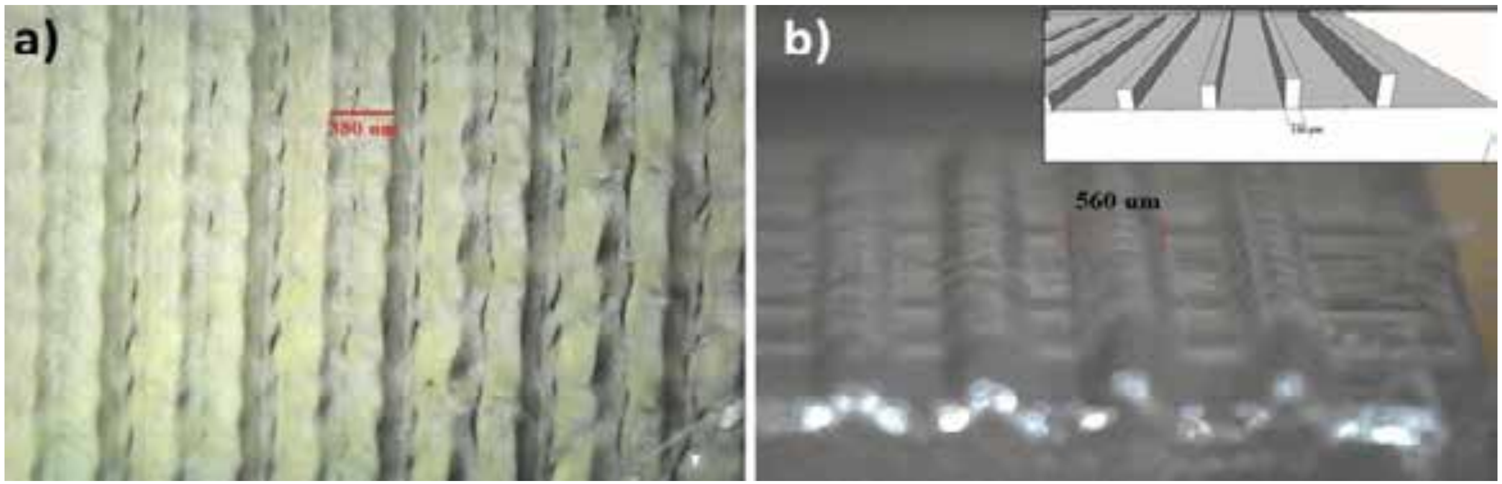
(a) FFF printed PP shows coarse hatching

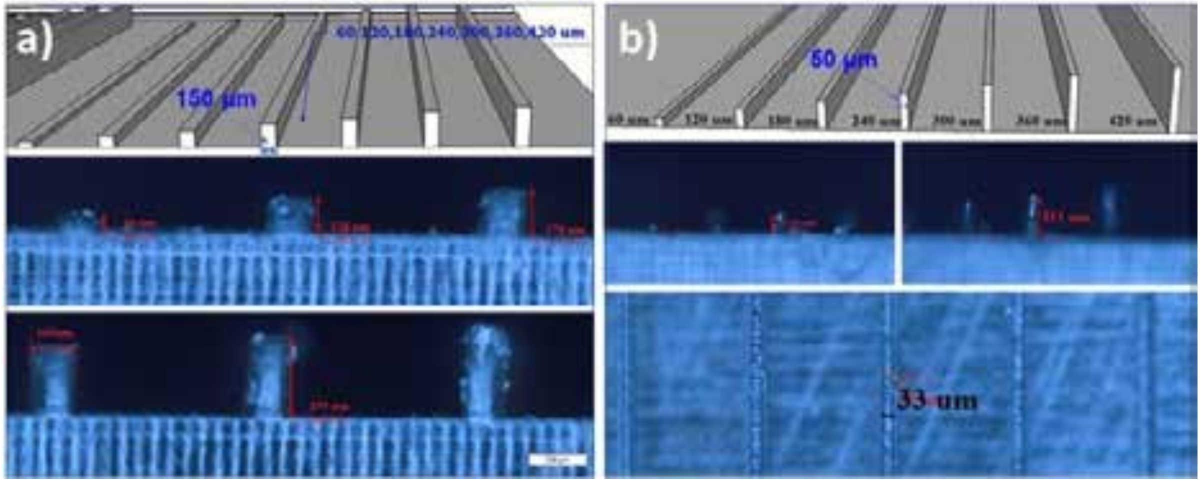
(b) Inkjet acrylics give smooth but rounded features

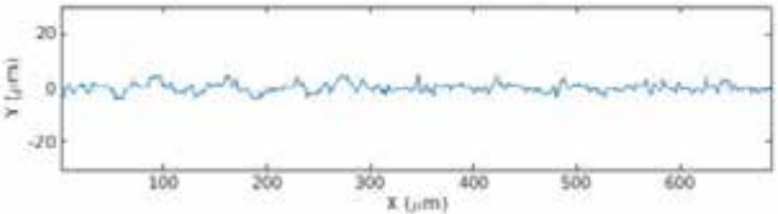


Process evaluation (2)

DLP processed acrylics give best print resolutions features down to < 50 µm

1.6 µm surface roughness





Exemplar AM optics

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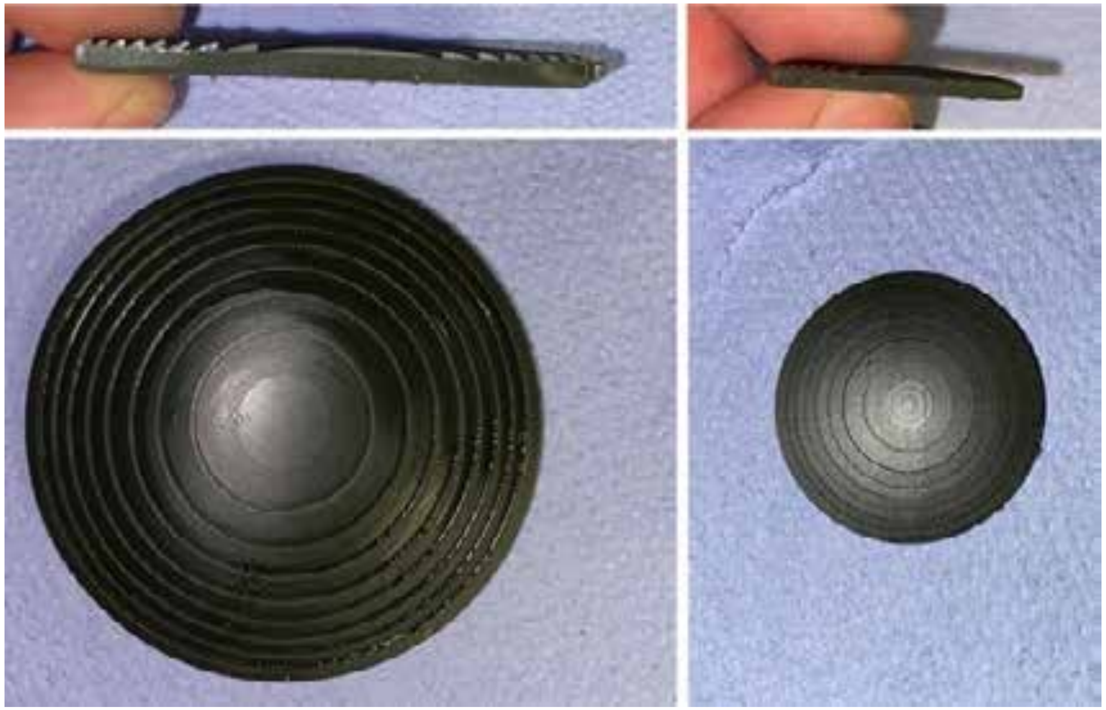
Exemplar THz Fresnel lens structures (1-mm groove pitch) fabricated



Liquid crystals

Classic LC materials

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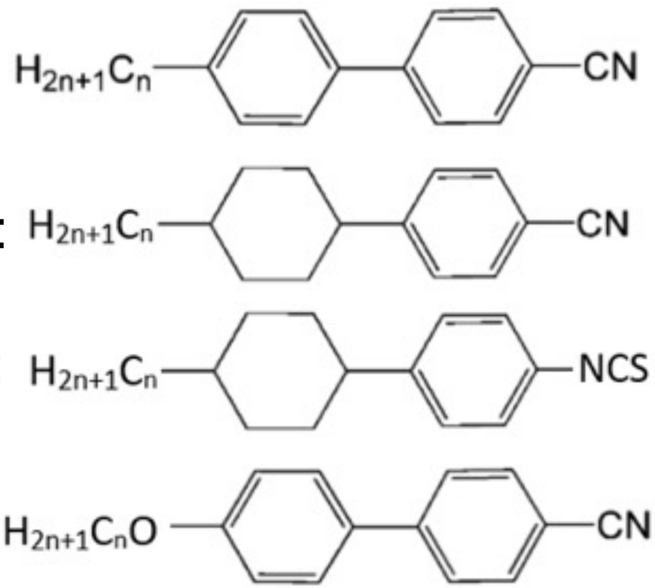
Many materials studied below 2 THz.

Commercial “E7” mixture gives good birefringence.

Material	Frequency/THz	n_o	n_e	Δn	Ref.
5CB	0.7-2.54	1.8~2.1	2.02~2.28	0.1~0.2	[1]
	0.1-0.8	1.62~1.67	1.75	0.08~0.13	[2]
	0.5-2.0	1.57~1.6	1.69~1.7	0.10~0.12	[3]
6CB	0.1-0.8	1.62~1.65	1.72	0.07~0.1	[2]
7CB	0.1-0.8	1.58~1.6	1.70	0.1~0.12	[2]
	0.5-2.0	1.55~1.58	1.68~1.69	0.11~0.13	[3]
E7	0.2-1.2	1.59~1.68	1.8	0.12~0.21	[4]
	0.2-2.0	1.55~1.57	1.7	0.13~0.15	[5]
PCH5	0.7-2.54	1.4~1.55	1.4~1.5	~0.05	[1]
	0.5-2.0	1.59~1.61	1.51~1.56	0.05~0.08	[3]
PCH7	0.5-2.0	1.59~1.61	1.51~1.56	0.05~0.08	[3]
5OCB	0.5-2.0	1.60~1.63	1.73~1.74	0.11~0.13	[2]
3CHBT	0.5-2.5	1.513~1.545	1.604~1.627	0.08~0.09	[6]
4CHBT	0.5-2.5	1.487~1.531	1.593~1.617	0.09~0.1	[6]
5CHBT	0.5-2.5	1.482~1.531	1.613~1.635	0.11~0.13	[6]
6CHBT	0.5-2.5	1.480~1.516	1.569~1.599	0.08~0.09	[6]
7CHBT	0.5-2.5	1.505~1.532	1.582~1.592	0.6~0.8	[6]
8CHBT	0.5-2.5	1.538~1.560	1.606~1.627	0.07	[6]
9CHBT	0.5-2.5	1.518~1.547	1.583~1.600	0.05~0.06	[6]
10CHBT	0.5-2.5	1.467~1.489	1.546~1.565	0.07~0.08	[6]
11CHBT	0.5-2.5	1.471~1.490	1.542~1.559	0.07	[6]
12CHBT	0.5-2.5	1.471~1.489	1.538~1.556	0.07	[6]

nCB: PCHn: nCHBT: nOCB:



[1] T. Nose, S. Sato, K. Mizuno, J. Bae, and T. Nozokido, Appl. Optics **36**, 6383 (1997).
[2] R. Wilk, N. Vieweg, O. Kopschinski, T. Hasek, and M. Koch, J. Infrared Millim. Terahertz Waves **30**, 1139 (2009).
[3] N. Vieweg, M. K. Shakfa, B. Scherger, M. Mikulics, and M. Koch, J. Infrared Millim. Terahertz Waves **31**, 1312 (2010).
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[5] C. S. Yang, C. J. Lin, R. P. Pan, C. T. Que, K. Yamamoto, M. Tani, and C. L. Pan, J. Opt. Soc. Am. B-Opt. Phys. **27**, 1866 (2010).
[6] U. Chodorow, J. Parka, and K. Garbat, Liq. Cryst. **40**, 1089 (2013).

LC cell design

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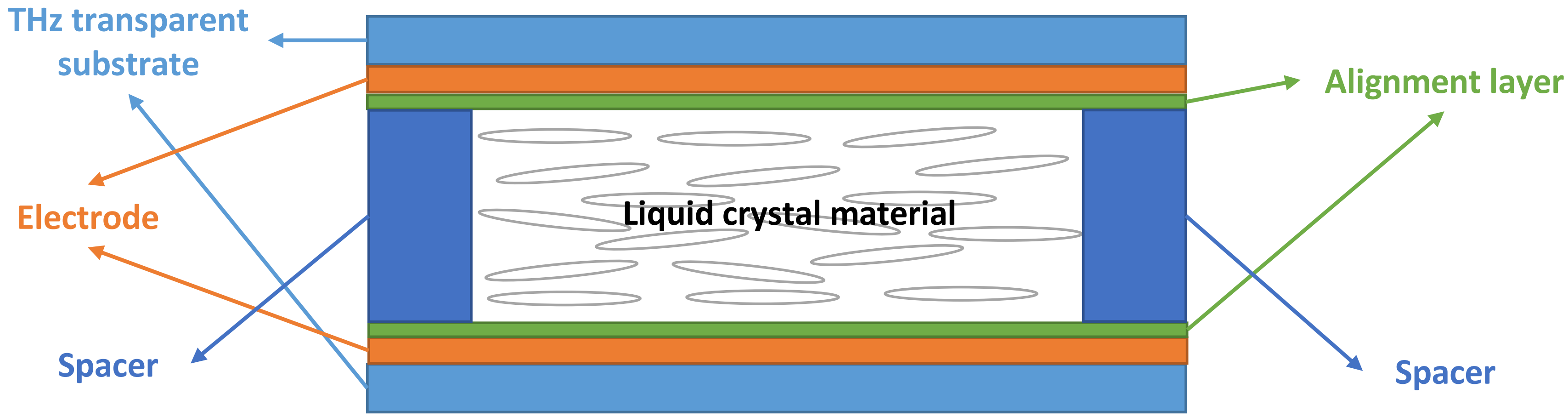
THz transparent materials needed!

Substrate - fused quartz
Electrodes - PEDOT:PSS conductive polymer
Alignment layer – polymide
Spacer – Melinex® (polyester film)



LC cell fabrication & test

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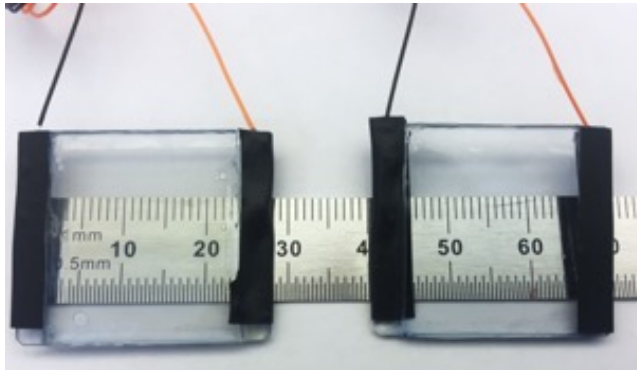
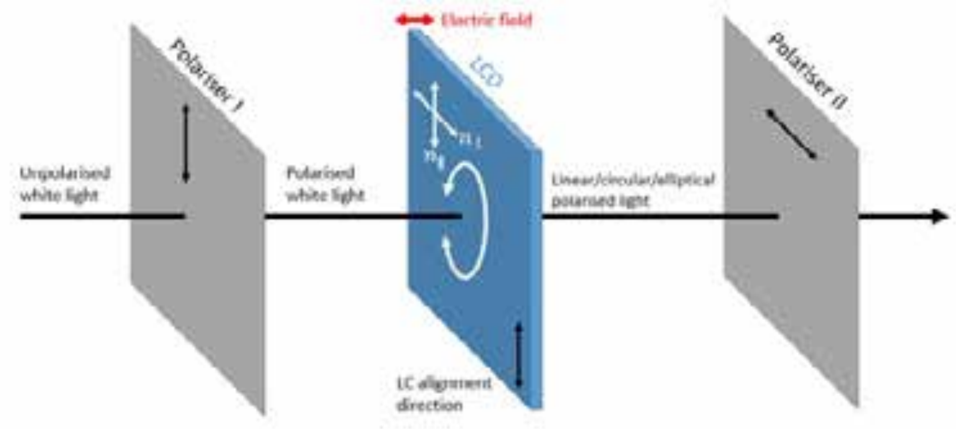
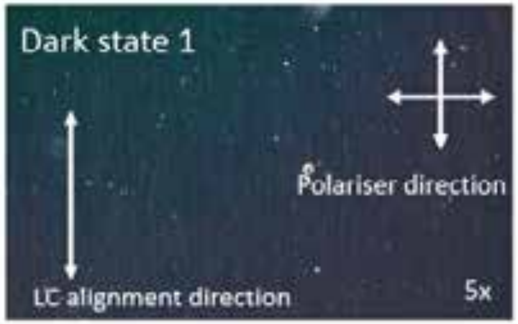
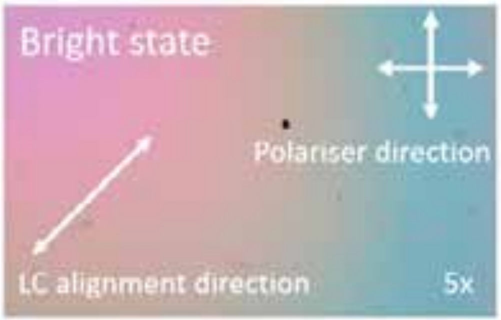
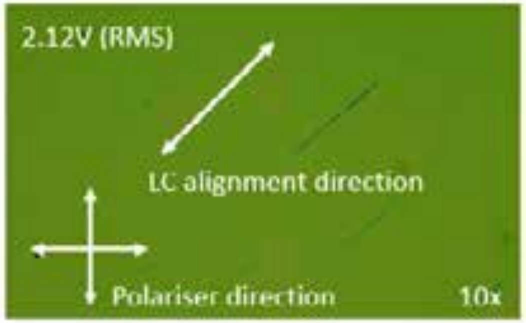
Optical measurements show uniform LC structure & strong response to applied field











THz TDS analysis

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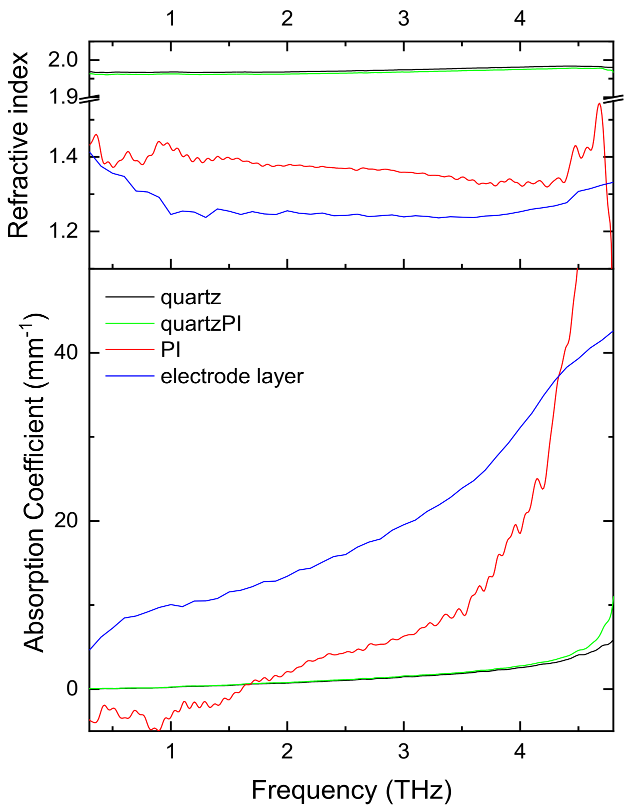
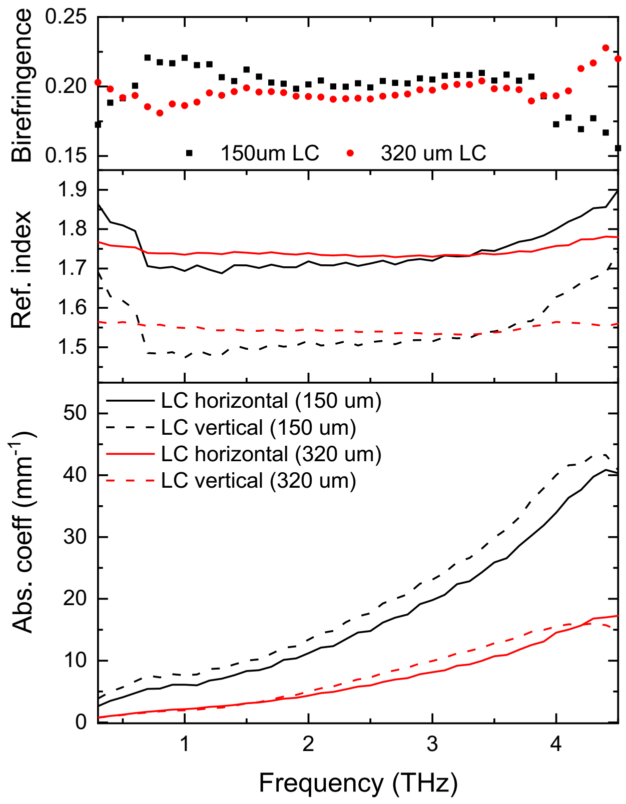
All materials THz transmissive up to >4.0 THz

Birefringence ~0.2 as expected





Electric field effects

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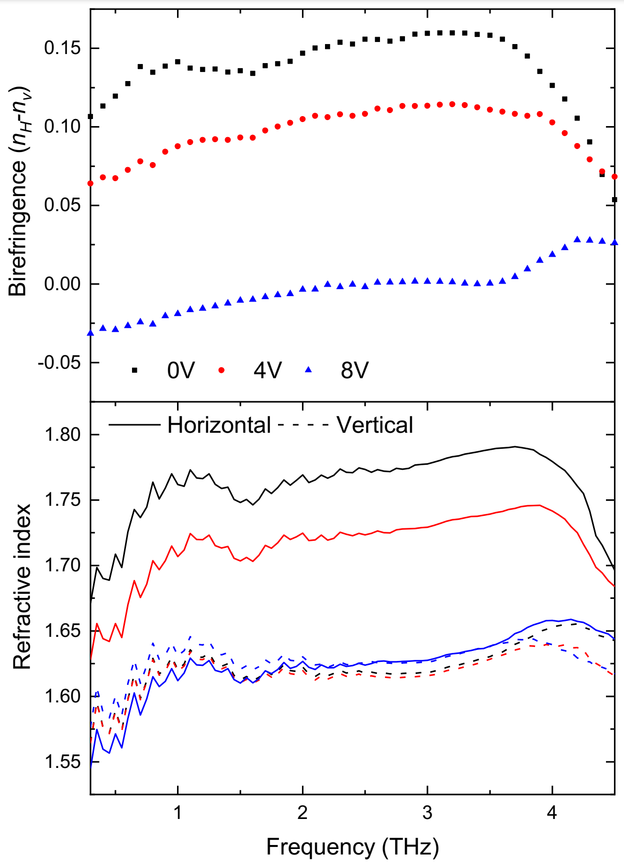
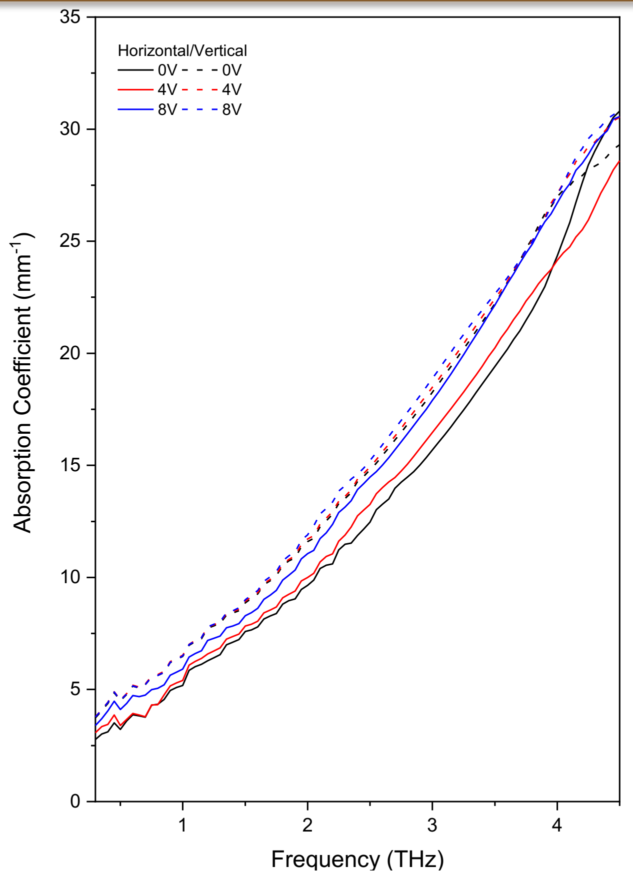
All materials THz transmissive up to >4.0 THz

Birefringence ~0.2 as expected





THz modulation study

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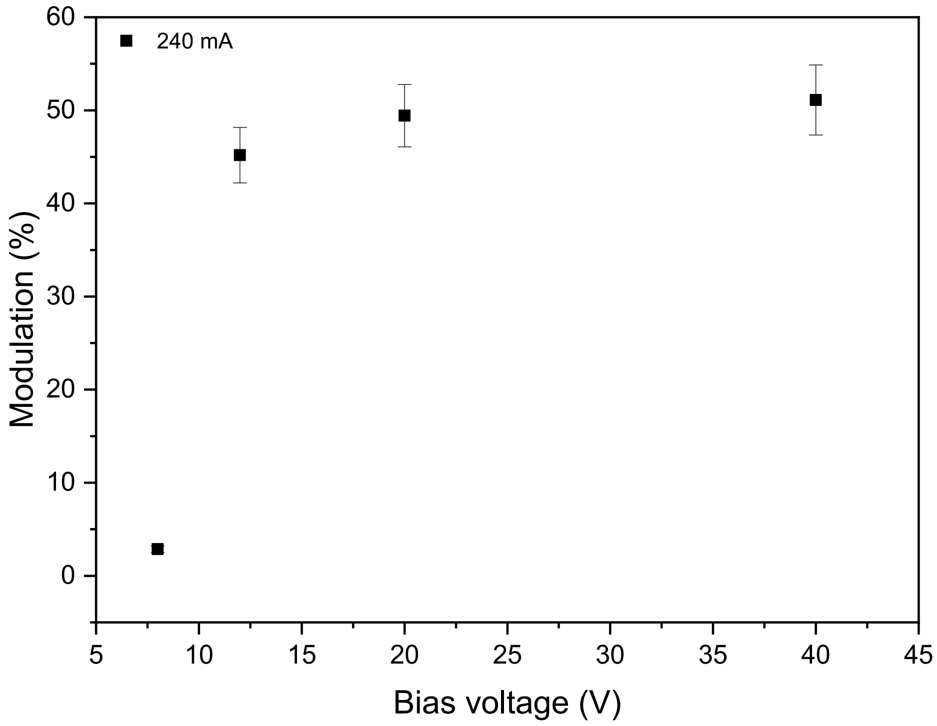
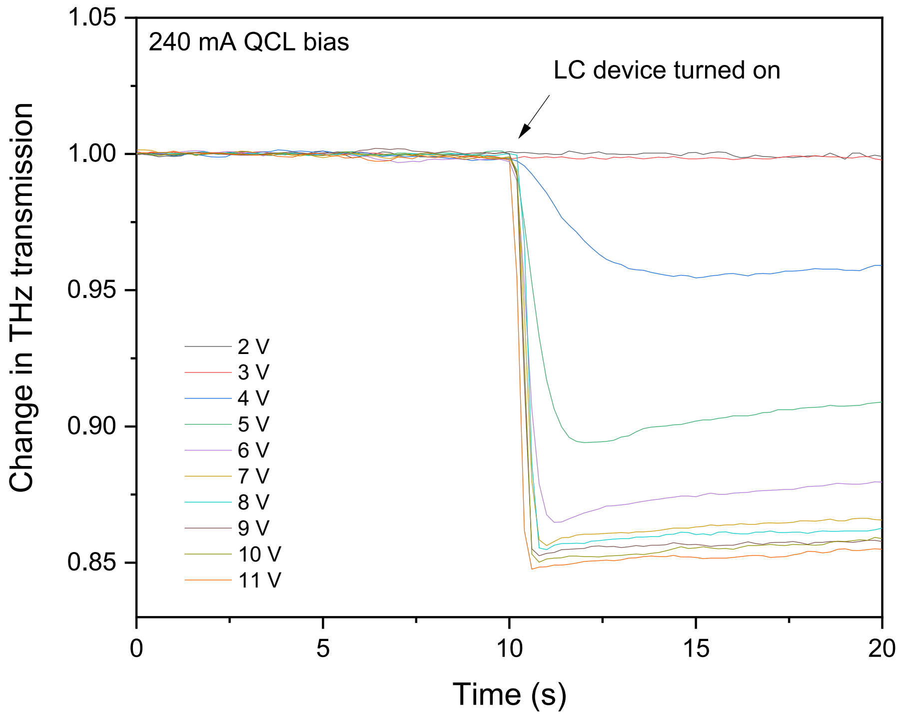
Large controllable transmission at 3.5 THz (up to 50%)

~1 s response achievable with thinner device





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Summary

Conclusions

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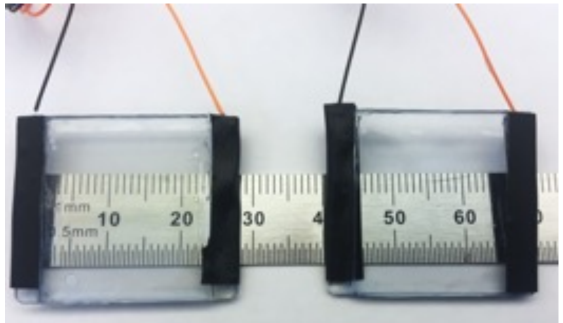
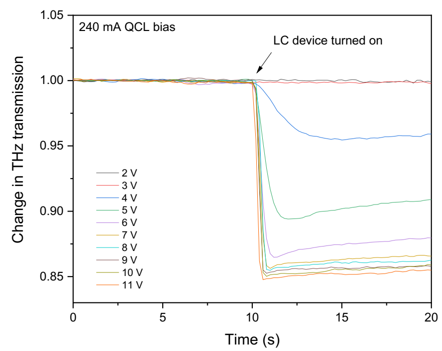
THz compatible AM materials & processes identified (separately!)

"E7" LC material provides good birefringence at > 2 THz



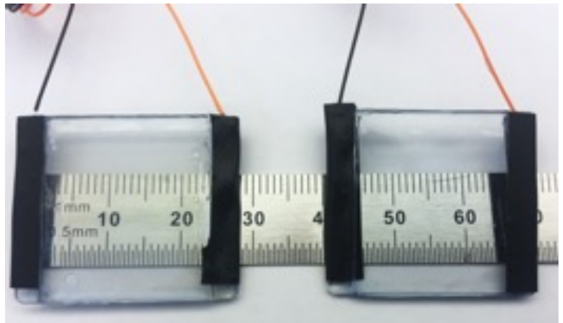
Exemplar LC device allows >50% 3.5-THz power modulation



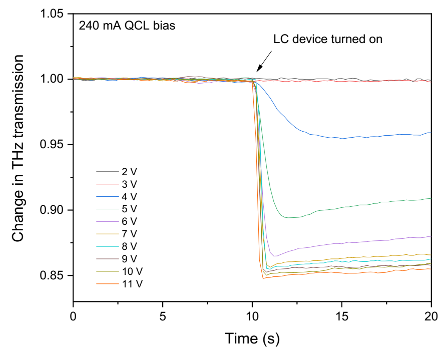
Next steps

Test emerging AM technologies; reflectors, calib. targets etc…

High-birefringence materials; fast multi-layer modulators



Spatial-light modulators; adaptive optics; metasurfaces…



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