Optimisation of Micro-Structured Waveguides in Lithium Niobate (z-cut)

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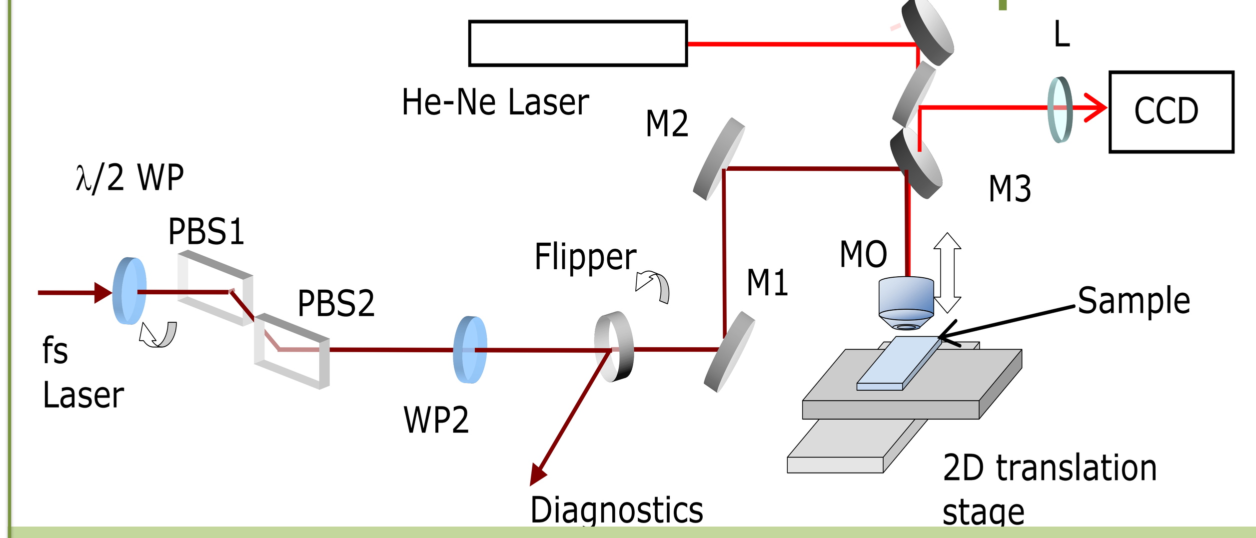
ABSTRACT: We describe how the guiding properties of buried, micro-structured waveguides that can be formed in a lithium niobate crystal by direct femtosecond laser writing can be optimized for low-loss operation in the mid-infrared region beyond 3.5 μm.

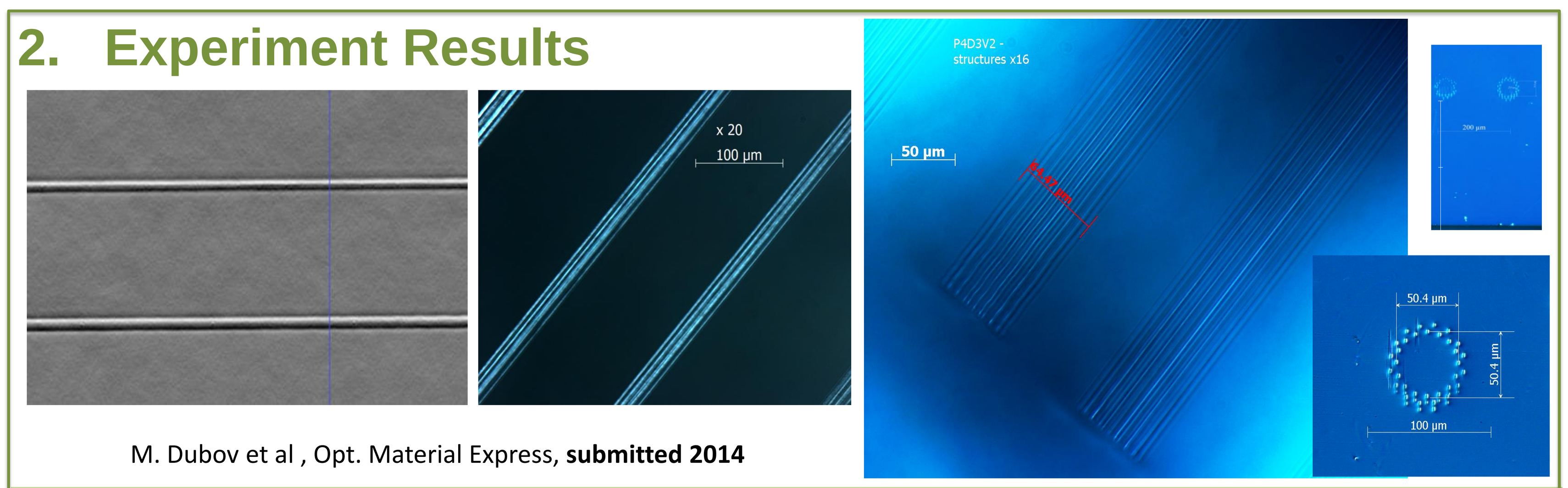
1. Direct Femtosecond Laser Inscription



Pulse Duration	~50 fs
Wavelength	792nm
Spectral width	30 to 35 nm
Repetition Rate	11 MHz
Pulse Energy	100 nJ
Average Power	1.1 W
Translation Speed	0.1μm/s to 0.1m/s
Shifts, H	10 μm to 2000 μm
NA	0.5 to 1.25 (oil)

Femtosecond Laser Inscription Set-up Layout

2. Experiment Results



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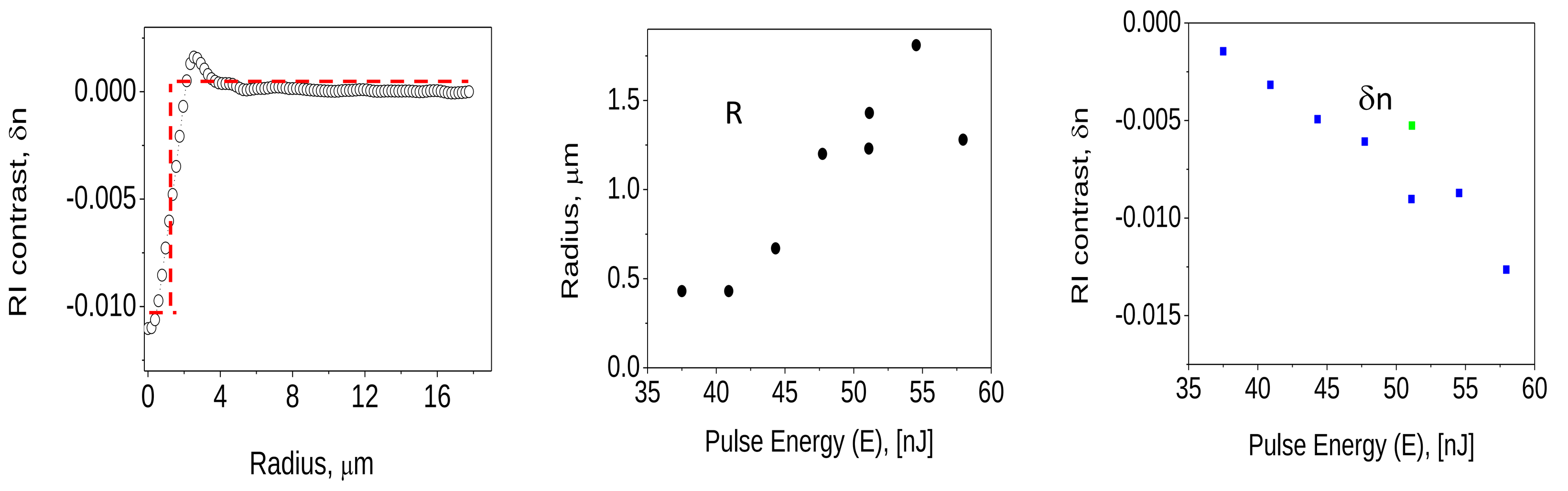
Individual tracks, micro-structured WG and its cross-sections

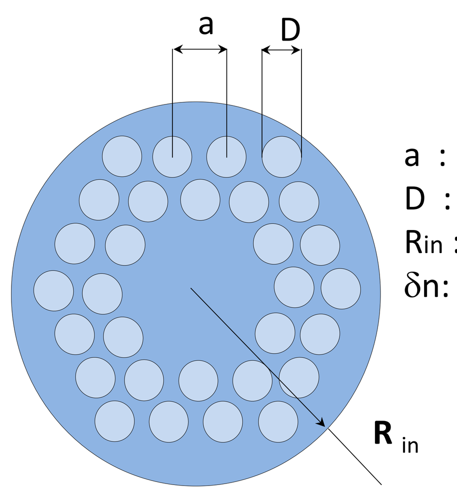
3. Parameters for Simulation

- The parameters measured were used in the simulations
- Step-index RI profile is assumed
- Both Radius and RI contrast of tracks are intra-dependent via Pulse Energy

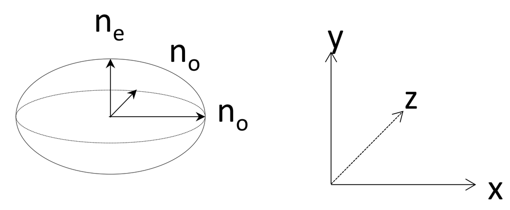


RI contrast vs Radius — Radius of Tracks *vs* Energy — RI contrast vs Energy

4. Numerical Calculation with COMSOL Muliphysics®

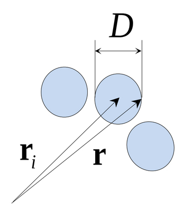


a : Track separation
D : Track diameter
Rin : Structure radii
δn: RI contrast



5%MgO:LiNbO$_3$ is negative uniaxial crystal (n_e < n_o), z-cut wafer, with the diameters of up to 4" and thickness of 0.5 or 1 mm.

Hexagonal Geometry



$\varepsilon_r = (n_{o,e} + \delta n)^2$, δn non-zero only in irradiated domain (uniform, not polarization and wavelength dependent)

- Wave Equation for Monochromatic Optical Wave in micro-structured WG:

$$\nabla\times\nabla\times\mathbf{E} - \omega^2\varepsilon_0\varepsilon_r\,\mu_0\,\mathbf{E} = 0, \qquad \varepsilon_r = \begin{pmatrix} \varepsilon_o & 0 & 0 \\ 0 & \varepsilon_e & 0 \\ 0 & 0 & \varepsilon_o \end{pmatrix}$$

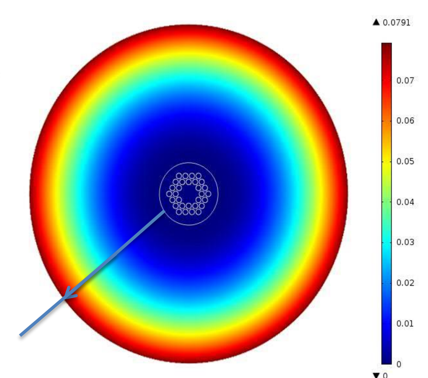
- Simulations are realized between 0.3 to 3 μm with 0.01 μm steps
- RI for congruently grown LiNbO3 taken from [Zelmon et al., JOSA B **14** 1997]
- PML and Mesh optimization is required for correct results

PML (Perfectly Matching Layer):

$$n_{PML}(r) = n_{o,e} - i\,k_{MAX}\left(\frac{r - r_{in}}{L}\right)^2, \quad r_{in} < r < r_{in} + L$$

$L = 40\mu m$

$k_{MAX} = 0.05$

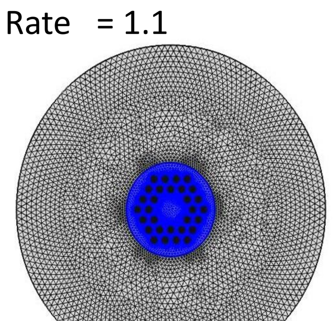


error $\sim \frac{1}{L^8}$

[Oskooi, *J.Comp.Phys.***230** (2011)]

MESH:

'Triangular' MESH
Max Mesh Size (at periphery) ~ 1 μm
Min Mesh Size (at core) ~ 0.003 μm
Growth Rate = 1.1



Parameters and Constrains for the numerical simulation

Period	a	>D/2	(2 μm to 5 μm)
Track Diameter	D	>0.5 μm	(0.08 μm)
RI Contrast	Δn	-0.02 ... -0.0005	(-0.05.....-0.01)
Cladding Layers	N_{clad}	>1	(1 to 7)

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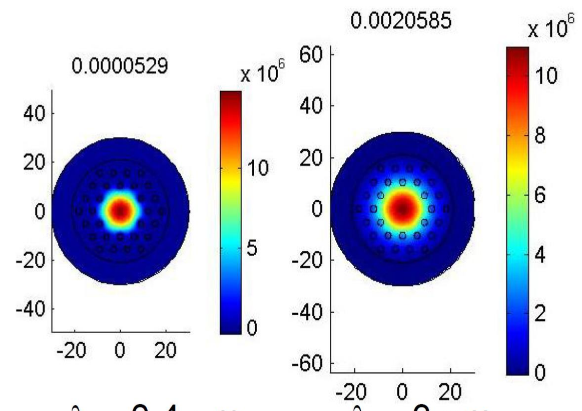
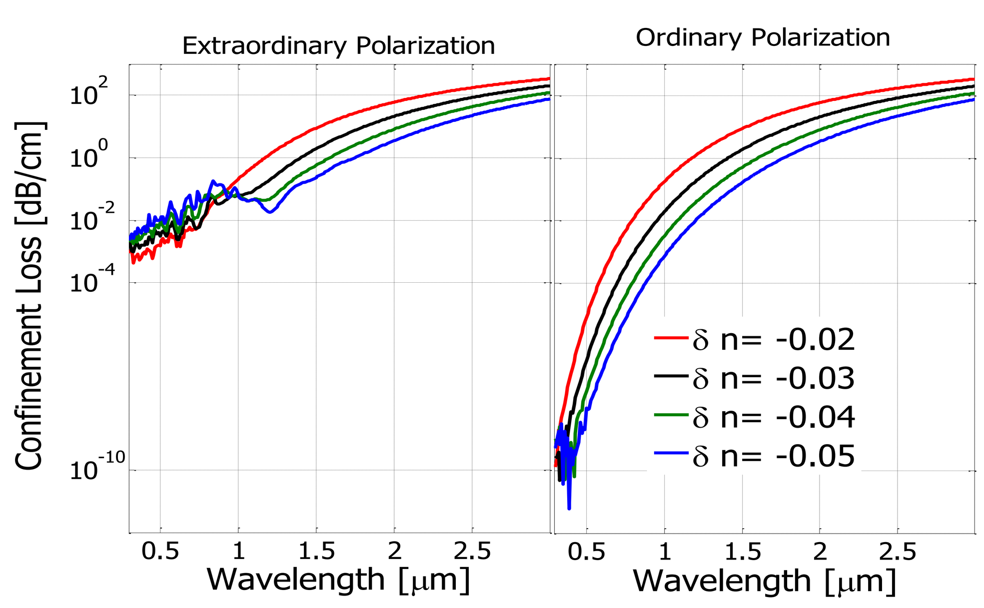
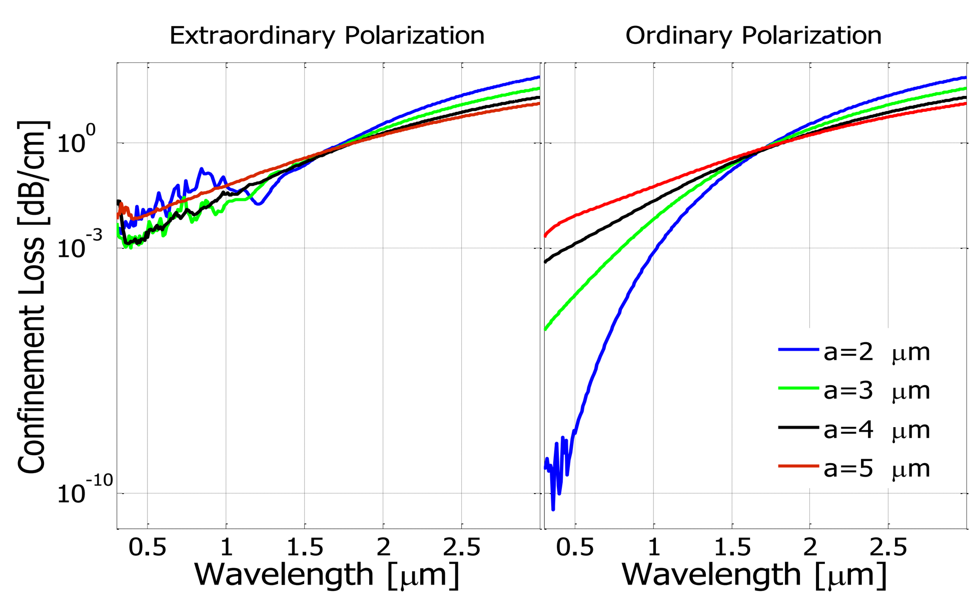


λ ~ 0.4 μm — λ ~ 3 μm

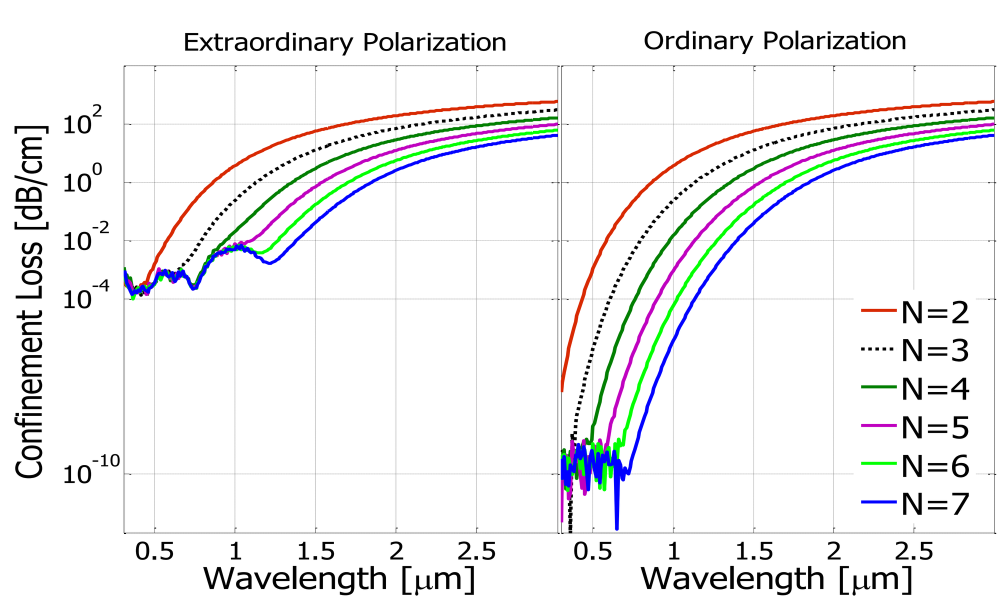
6. Results



Effect of change of RI contrast
(*D* = 1.6 *μm*, N $_{clad}$ =2, *a* = 2 *μm* , δn = variable)



Effect of change of track radii
(δn = - 0.01, *D* = 1.6 *μm*, N $_{clad}$ =2, *a* = variable)



Effect of change of number of cladding layers
(δn = - 0.01, *D* = 1.6 *μm*, *a* = 2 *μm* , N $_{clad}$ – variable)

7. Optimisation

Minimum confinement loss is searched by changing the track diameters of each layer according to the formula:

$$D(N) = D_{min} + 2\cdot\left(\frac{N-1}{N_{clad}-1}\right)^p\cdot(D_{max} - D_{min})$$

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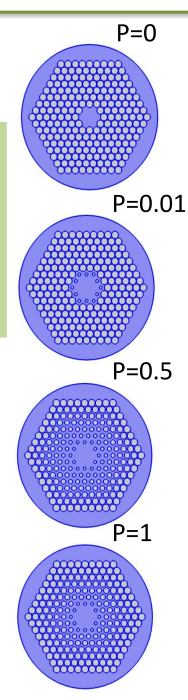
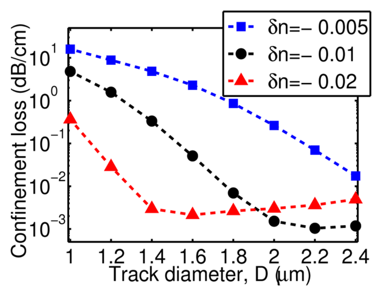
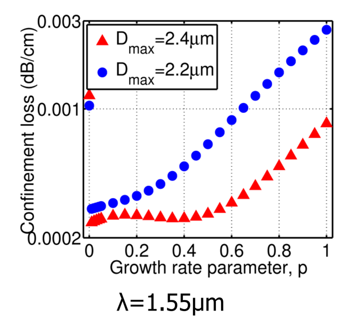
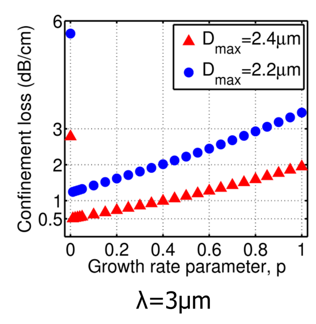




a=2.5μm, 7-ring structure, δn - variable

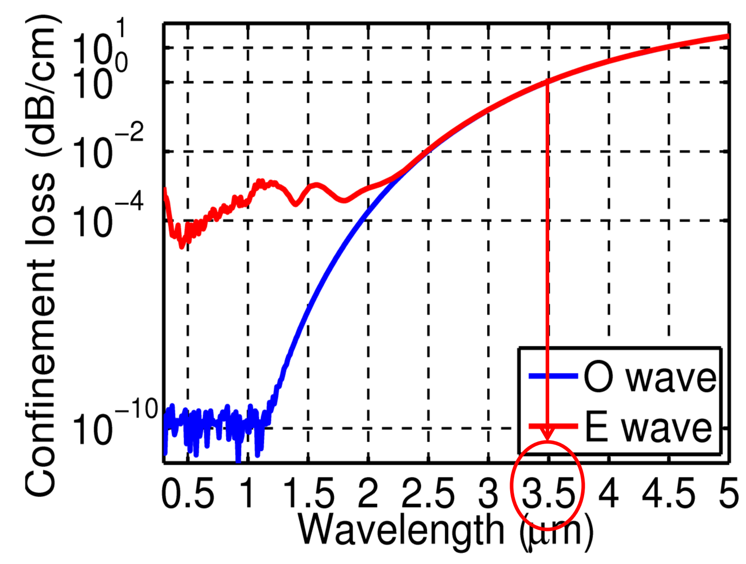
Confinement loss at λ=1.55μm for *e*-polarisation versus track diameter for a seven-ring (uniform) WG structure.





7-rings,
δn = −0.01
D_{min} = 1μm

Confinement loss for *e*-polarisation versus growth rate parameter, *p*.



RI contrast:
δn = - 0.01,
Dmin = 1.0 μm,
Dmax = 2.4 μm,
p = 0.01

Losses for o- and e-waves for 7-ring WG structure with variable RI contrast, changing from one ring to another, following the change in track size.

CONCLUSIONS: We have numerically demonstrated that the guiding properties of depressed-cladding, buried WGs formed in a LiNbO3 crystal by fs laser writing can be controlled by the WG structural characteristics, even for the relatively moderate induced RI contrasts typical of the direct fs inscription. In particular, the number of depressed-cladding layers has revealed to play a major role in the control of the WG properties. Importantly for practical applications, we have shown that for an induced RI contrast of -0.013, the propagation losses can in principle be reduced by four orders of magnitude at telecom wavelengths by increasing the number of cladding layers from 2 to 7. Minimisation of the confinement loss at mid-infrared wavelengths is realised by varying the growth rate of track diameters.

Excerpt from the Proceedings of the 2014 COMSOL Conference in Cambridge