Accurate modelling of femtosecond-laser direct written fibre Bragg gratings

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Femtosecond laser inscribed point-by-point (PbP) Bragg gratings are a distinct class of fibre Bragg gratings with unique characteristics and morphology [1] compared to conventional holographically-inscribed gratings. These characteristics are determined by the interaction of very compact ($d < 1$ μm), high index contrast ($\Delta n \approx 0.4$) grating damage sites (Fig. 1a) with the spatial profile of the fibre modes. These strong features can strongly distort the optical mode profile (Fig. 1b), potentially invalidating the standard assumptions of coupled mode theory (CMT). We investigate this by modelling PbP gratings with CMT and an exact Bloch function approach (treating the device as a photonic bandgap structure) and compare both with experimental results.

We inscribed second order PbP gratings at 1550 nm with a period of 1.06 μm inside OFS two-mode graded index fiber using an 800 nm femtosecond laser emitting 120 fs long pulses at 100 Hz repetition rate with pulse energy in the range of 110 to 210 nJ [2]. We estimated experimental coupling strengths κ_{exp} from reflection spectra. To model the gratings, we extracted the grating dimensions (Fig. 1a) and refractive index profile with scanning electron microscopy and micro-reflectivity measurements respectively, and then used this data in standard CMT expressions to obtain the coupling coefficient κ_{CMT}. For the rigorous Bloch function approach, we created a 3D model in COMSOL using periodic boundary conditions over a single grating period (Fig. 1c) . By sweeping the wavevector over the first Brillouin zone we estimated the frequency gap of band edge states and thus obtained $\kappa_{\text{Bloch}} = \Delta\omega/2v_g$. Figure 1d compares the κ values associated with LP_{01}−LP_{01} coupling. Clearly the Bloch function approach performs much better, especially for strong defects at large writing power.

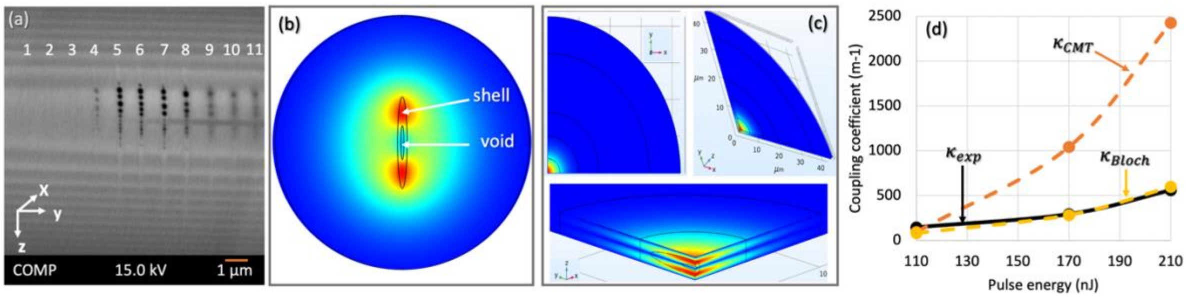

Figure 1: PbP grating (a) SEM image, (b) Distorted LP_{01} mode, (c) 3D model, (d) κ vs laser pulse energy.

With CMT, the expulsion of the field from the centre of the damage site is not accounted for, leading to over-estimation of the coupling strength. The Bloch function approach correctly accounts for the distorted mode profile in a self-consistent fashion and provides a more accurate picture of the PbP grating dynamics, and a valuable tool for inferring information on the shape of the grating defects. This limitation of CMT is well-known, but it is rare to find a fibre where the discrepancy from an exact treatment is so marked.

[1] J. U. Thomas et al., *Opt. Express* **20**, 21434 (2012).

[2] S. Bhardwaj et al., *Opt. Lett.* ***47**, 453 (2022).*