Opto-mechanical responses of 3D TiO$_2$ inverse opal structured photonic crystal strain sensors

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ABSTRACT

Three-dimensional (3D) photonic crystals (PCs) are attractive periodic structures in optoelectronic applications because of their selective reflection of lights with frequencies within the photonic band gap (PBG). Inverse opals of high refractive index TiO$_2$ ($n = 2.8$) with face centered cubic lattice of air ($n = 1$) spheres are candidates for strain sensors due to shifts of the PBG triggered by mechanical strains. In order to quantify the relations between applied strains and the peak reflectance wavelength of opal PCs, finite element method (FEM) and 3D finite-difference time-domain (FDTD) calculations are carried for conditions of uniaxial compressive strain. The FEM calculations yield deformed geometries and stress fields, allowing the evaluation of changes in the PBG due to both deformation and stress-induced shifts in the refractive index of the material. The calculation of shifts in the index of refraction fields is via the opto-mechanical constitutive relations. A maximum principal stress failure criterion is used to determine the overall elastic limit of the PC structures. The 3D FEM and FDTD simulations yield the shifts in the peak reflectance wavelength. It is found that the wavelength at the peak reflectance can decrease by up to 2.6 nm for deformations up to the elastic limit strain (~0.7%). The changes in the reflectance spectrum are almost exclusively due to deformation (changes in size and geometry) of the inverse opals and stress-induced shifts in the refractive index fields (~0.6%) are too small to have an appreciable impact on the optical response. The strain-optical response relations obtained can be used to develop TiO$_2$ PC strain sensors.