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Ultrahigh piezoelectricity in ferroelectric ceramic truss-based metamaterial

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ABSTRACT

Conventional porous ferroelectric materials sacrifice their piezoelectric constants to improve various figures of merit due to a rapidly decreased dielectric constant. Here, we have proposed a strategy for developing lattice ferroelectric metamaterials with ultrahigh piezoelectricity, diverse anisotropic piezoelectric properties, and exceptional ferroelectric figures of merit, all driven by their underlying microarchitecture. Regardless of material composition, this design approach applies to any ferroelectric ceramics with a similar piezoelectric constant matrix, validated through modified asymptotic homogenization, analytical derivation, and experimental testing using a custom ceramic 3D printing platform. The unprecedented piezoelectric characteristics originate from the unique combination of truss loading states and polarization direction. Based on the deformation mode, two types of lattices are considered: the bending-dominated tetrakaidecahedron and the stretching-dominated octet truss. The former carries load primarily through the bending of its ligaments or struts, while the latter deforms mainly through uniaxial compression or tension, resulting in a mechanically more efficient design.

Unlike porous ferroelectrics, we attain enhanced piezoelectric constants at low relative densities ($\rho_r \sim 0.1$). For example, with appropriate scaling, the experimental values of d_{31}, d_{33}, and d_{42} for a ferroelectric octet truss based on $BaTiO_3$ ceramic with $\rho_r = 0.1$, can reach 849 pC/N, -659 pC/N, and 836 pC/N, respectively, which are 3.14, 6, and 2 times higher than the corresponding piezoelectric constants in the bulk state. This enhancement can be theoretically predicted as being inversely proportional to the sine of the truss inclination angle, which amplifies the axial force experienced by the truss. Achieving this maximum optimized value requires reducing the relative density to satisfy the beam model. Consequently, both decreasing the relative density and scaling the stretching-dominated truss along the polarization direction contribute to achieving these giant values. Combined with the ultralow dielectric constant, extremely high ferroelectric figures of merit, e.g., piezoelectric voltage constant of 11.098 Vm/N, piezoelectric energy harvesting figure of merit 9422×10^{-12} m²/N, and pyroelectric voltage sensitivity of 56.7×10^{-3} m2/C, are observed in the 3D printed rationally designed ferroelectric metamaterials. We deem our programmable multifunctional ferroelectric lattice metamaterials represent the next generation of architected piezoelectric materials, with versatile applications ranging from energy-absorbing structures and ultrasensitive force/thermal sensors to wearable self-powered input devices and precisely controlled microelectromechanical systems.