Abstract

The rapid development of photonics following the invention of the laser has profoundly transformed optical communication, sensing, and signal processing technologies. Among various photonic platforms, optical fibers and artificially engineered resonant metasurfaces have emerged as versatile systems for controlling light-matter interaction over a broad range of frequencies. In recent years, there has been growing interest in exploiting 3rd order nonlinear optical phenomena in centrosymmetric media, driven by their fundamental importance and potential applications in ultrafast optics, frequency conversion, and terahertz (THz) technologies. However, the inherent weakness of 3rd order nonlinear effects demands advanced strategies for enhancing and controlling nonlinear response through waveguide design, dispersion engineering, and strong electromagnetic field confinement.

This thesis presents a systematic study of 3rd order nonlinear optical phenomena in guided-wave and resonant metasurface platforms, with primary emphasis on Kerr nonlinearity in optical fibers and nonlinear frequency conversion processes such as third-harmonic generation (THG) and four-wave mixing (FWM) in THz metasurfaces. The work begins with the development of a general and self-consistent numerical algorithm based on a finite-difference eigenvalue formulation to analyze wave propagation in optical fibers with arbitrary refractive index profiles. Unlike conventional analytical or semi-analytical methods that rely on profile-specific approximations, the proposed approach directly solves the Helmholtz equation without assuming any trial modal field. Linear modal characteristics are first validated for standard step-index, graded-index, and complex refractive index profiles, establishing the accuracy and generality of the method. Subsequently, 3rd order Kerr nonlinearity is incorporated through an intensity dependent refractive index, enabling self-consistent nonlinear modal analysis. Using the same framework, material dispersion, waveguide dispersion, and total dispersion are evaluated, allowing detailed investigation of nonlinear dispersion shifting and dispersion flattening. The results demonstrate broadband dispersion flattened behavior near the zero-dispersion wavelength, which enables pulse propagation with minimal temporal distortion and is crucial for nonlinear and ultrafast fiber applications. The numerical predictions show excellent agreement with full wave COMSOL simulations, while offering significantly reduced computational cost, making the method suitable for long-length fiber analysis.

Extending the concept of nonlinear response engineering from guided-wave systems to resonant metasurface structures, the thesis next explores frequency-selective THz metasurfaces based on complementary split-ring resonator (C-SRR) geometries. The C-SRR acts as a parallel LC resonator that couples dominantly to the electric field and produces a strong electric resonance associated with effective permittivity. This strong field confinement is exploited to enhance 3rd order nonlinear interaction in the THz regime, where intrinsic nonlinear response is typically weak. To achieve dynamic tunability without structural redesign or re-fabrication, graphene is introduced as the nonlinear medium due to its exceptionally large 3rd order susceptibility and its Fermi-energy tunability in THz frequencies. An electromechanically tunable graphene based metasurface is proposed, where mechanical deflection of a suspended graphene layer under low applied voltages modifies the resonant condition. Further enhancement is realized by integrating graphene micro-cantilevers with C-SRR structures, combining strong electric field localization with electromechanical tunability to achieve efficient and continuously tunable THz THG at low excitation intensities.

Finally, the thesis advances to the realization of a more general 3rd order nonlinear process FWM in the THz regime. A wideband graphene metasurface is designed to demonstrate mode-selective dual-band THz FWM, highlighting the capability to engineer broadband linear response alongside selective nonlinear emission. Overall, this work establishes unified theoretical and numerical strategies for controlling 3rd order nonlinear optical phenomena across guided-wave and resonant metasurface platforms, with potential applications in fiber-optic systems, THz sources, and reconfigurable nonlinear photonic devices.

Keywords: *Third-order nonlinear optics, Optical Kerr effect, Nonlinear optical fibers, Dispersion engineering, Terahertz metasurfaces, Complementary split-ring resonator, Graphene nonlinearity, Electromechanical tunability, Third-harmonic generation, Four-wave mixing*