Full vibrational spectroscopy for simultaneous mechanical, structural and chemical analysis

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Comprehensive characterization of materials across mechanical, structural, and chemical domains is essential in applications ranging from pharmaceutical manufacturing to life and materials sciences. Conventional vibrational spectroscopy techniques are typically limited to specific spectral windows, restricting the amount of correlated physical information that can be extracted from a single measurement. Here, we present an all-optical, non-destructive, and label-free method capable of acquiring the full vibrational spectrum of a material, spanning from the Brillouin and ultra-low-frequency Raman (ULFR) regimes to conventional Raman frequencies (0.1 cm^{-1} - 3,500 cm^{-1}). A birefringence-induced phase delay (BIPD) filter [1] with an optimized free spectral range provides high suppression (~60 dB) of the elastic background light and enables the simultaneous acquisition of Brillouin, ULFR, and Raman spectra from the same illumination voxel.

The application potential of this approach is demonstrated through solid-state form analysis of active pharmaceutical ingredients (APIs), where reliable differentiation of crystalline and amorphous forms is crucial for controlling solubility, bioavailability, and manufacturability [2]. Simultaneous access to mechanical (Brillouin), structural (ULFR), and chemical (Raman) information provides a multidimensional spectral fingerprint that significantly enhances sensitivity and selectivity compared to the individual techniques. Full-vibrational spectroscopy enables discrimination between amorphous phases prepared under different conditions. Studies on indomethacin and indomethacin–PVP blends further demonstrate that Brillouin spectroscopy offers increased sensitivity at higher mixture concentrations, complementing Raman and ULFR analyses.

Beyond single point spectroscopy, the system is extended to full-vibrational imaging. Full-spectral mapping of pharmaceutical tablets enables accurate microscale identification of APIs and excipients while simultaneously revealing their mechanical and structural heterogeneity. This approach opens new opportunities for real-time, quantitative characterization and quality control in pharmaceutical manufacturing, with broader potential in life sciences and materials research through fully optical, label-free, three-dimensional multimodal imaging [3].

References

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