Structure–Property Relationships Governing Dielectric Dissipation Factor in Polyimides across GHz–THz Frequencies

Haonan LIU[1], Ririka SAWADA[1], Hiromichi HOSHINA[2], and Shinji ANDO[1]

[1] School of Materials and Chemical Technology, Institute of Science Tokyo,

[2] Center for Advanced Photonics, RIKEN

Polyimides (PIs) are promising dielectric materials for 5G/6G applications due to their thermal stability and low dielectric loss. However, the origin of the dissipation factor (D_f) across the GHz–THz range remains unclear. In this study, broadband dielectric properties (10–330 GHz) and terahertz (THz) absorption spectra (1–10 THz) were systematically investigated for various aromatic PIs, including highly fluorinated systems.[1–3] The D_f increases monotonically with frequency, and both its absolute value and dispersion strongly depend on molecular structure. The absence of distinct relaxation peaks in the GHz region indicates that D_f is dominated by the low-frequency tail of vibrational and relaxation modes extending from the sub-THz/THz regime rather than discrete dipolar relaxations.

THz spectroscopy reveals characteristic absorption bands arising from backbone vibrations and intermolecular interactions, whose distribution reflects chain rigidity, symmetry, and packing structure. Rigid and highly ordered PIs exhibit sharp, localized absorption features, whereas flexible or disordered systems show broad and distributed spectra, indicating a wider distribution of vibrational states.

A clear correlation is observed between THz absorption and dielectric response: polymers with broader THz absorption exhibit higher D_f and stronger frequency dispersion, while those with localized vibrational modes show suppressed D_f and weaker dispersion. This relationship demonstrates that both the magnitude and frequency dependence of D_f are governed by the distribution and anharmonicity of vibrational modes in the THz region.

These results provide a unified picture linking molecular structure, THz vibrational dynamics, and broadband dielectric loss, and highlight molecular rigidity, symmetry, and dense packing as key factors for minimizing D_f in high-frequency polymer dielectrics.

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References

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