2. Broadband (10–330 GHz) Dielectric Characterization of Polyimides for High-Frequency Communication Applications

Haonan LIU, Ririka SAWADA, Yoshiyuki TSURUSAKI, Shinji ANDO*

Department of Chemical Science and Engineering, Institute of Science Tokyo, Japan
* ando.s.aa@m.titech.ac.jp

Abstract: Insulating materials with low dielectric constant (D_k) and low dissipation factor (D_f) are vital for high-frequency electronic devices, especially in 5G and forthcoming 6G wireless communication systems operating in the millimeter-wave range (30–300 GHz). Polyimides (PIs) are attractive candidates owing to their thermal stability, mechanical robustness, and environmental durability. However, their dielectric behavior above 100 GHz remains insufficiently investigated, limiting their practical use in next-generation applications. In this study, we employed Fabry–Pérot resonators [1] to systematically measure the dielectric properties of a broad range of PIs across 10–330 GHz. The evaluated samples include commercial PIs, bio-based PIs, partially and highly fluorinated PIs (FPIs), and sulfur-containing PIs (SPIs). A gradual decrease in D_k was observed with increasing frequency, statistically approaching the refractive index squared (n^2) in the near-infrared region. In contrast, D_f increased linearly with frequency at varying rates, suggesting that low D_f at low frequencies does not necessarily translate to high-frequency performance [2]. The absence of distinct absorption peaks throughout the frequency range implies that no significant relaxation processes occur, with dielectric dispersion dominated by localized chain motions. Among the studied materials, Kapton exhibited relatively high dielectric losses (D_k > 3.4, D_f > 0.015 at 300 GHz). By contrast, FPIs showed superior characteristics, with D_k < 2.8 and D_f < 0.01 at 100 GHz and < 0.015 at 300 GHz. Notably, PIs containing 2,2'-bis(trifluoromethyl)benzidine (TFDB) units displayed increased D_f values, underscoring the influence of molecular structure on high-frequency dielectric performance. Further evaluation using a custom-built humidity-controlled dielectric measurement system at 10 GHz demonstrated that all FPIs maintained low D_k and D_f under 60% relative humidity, whereas Kapton showed elevated values ($D_k \approx 3.6$, Df ≈ 0.02) [3]. This indicates that the low polarizability and reduced water uptake of FPIs contribute to their excellent dielectric stability under humid conditions. Additionally, SPIs exhibited relatively high D_k but low D_f, especially those with multiple thioether linkages, which showed D_f values comparable to FPIs and low humidity sensitivity. These findings underscore the potential of both FPIs and SPIs for high-frequency applications under demanding conditions.

Keywords: Dielectric constant, Dissipation factor, Fluorine, Sulfur, Bio-based, Humidity dependence, High frequency, Wireless communication

[1] EM Labs Inc., Japan, www.emlabs.jp; [2] H. Liu, R. Sawada, S. Yanagimoto, Y. Yanagimoto, S. Ando, Appl. Phys. Lett. 2024, 124, 232903; [3] R. Sawada, S. Ando, J. Phys. Chem. C, 2024, 128, 6979.

3. 高频低介电常数、低介电损耗改性聚酰亚胺（MPI）的研究

Study on the Modified Polyimide (MPI) with Low Dielectric Constant and Low Dielectric Loss at High Frequency

谭婉怡 *，张辉，袁慧波，胡慧珊，崔婷婷，闵永刚 *

广东工业大学，广州市番禺区广州大学城外环西路 100 号，510006

Wanyi Tan* , Hui Zhang, Huibo Yuan, Huishan Hu, Tingting Cui, Yonggang Min*

Guangdong University of Technology (GDUT), Guangzhou 510006, P. R. China
*tanwanyi@gdut.edu.cn；ygmin@gdut.edu.cn

摘要：随着 5G 通信技术的迅速发展，对于低介电常数（D_k）、低介电损耗正切（D_f）的介电材料的需求在不断增加。其中，改性聚酰亚胺（MPI）具有出色的热稳定性、化学稳定性和机械性能，是适用于高频通信的重要介电材料之一。增强聚合物链的刚性和分子间相互作用能够有效限制分子的取向极化，确保材料在高频下具有低介电常数和低介电损耗。近年来，我们通过在聚酰亚胺主链中引入软 - 硬段结构，平衡聚合物链的刚性和链之间的紧密堆积，从而有效降低介电常数和介电损耗至 3.02/0.0044 @ 10 GHz。此外，我们也通过调控分子链刚性及二胺单元的给电子特性，在不形成氢键和交联的情况下，提升聚酰亚胺的热稳定性，如玻璃化转变温度为 445 ℃，热膨胀系数降为 5 ppm K^{-1}，这有利于提升通信设备运行的可靠性。

关键词：改性聚酰亚胺，介电性能，热膨胀系数

Abstract: With the rapid development of 5G communication technology, the demand for dielectric materials with low dielectric constant (D_k) and low dielectric loss tangent (D_f) is constantly increasing. Among them, modified polyimide (MPI) is considered as one of the important dielectric materials for high-frequency communication, owing to its excellent thermal stability, chemical stability and mechanical properties. Enhancing the rigidity of polymer chains and intermolecular interactions can effectively restrict orientation polarization, endowing MPI with low dielectric constant and low dielectric loss at high frequency. In recent years, we develop MPI with soft-rigid structure, which effectively balances the trade-off between the rigidity of polymer chains and the chain packing density. As a result, the as-prepared MPI achieves a low D_k/D_f of 3.02/0.0044 @ 10 GHz. Furthermore, we have also improved the thermal stability of polyimide by regulating the chain rigidity and the electron-donating properties of diamine, without forming hydrogen bonds or crosslinking. The resultant PI possesses a glass transition temperature (Tg) of 445 ℃ and a thermal expansion coefficient (CTE) of 5 ppm K^{-1}, which contributes to enhancing the operational reliability of communication equipment.

Keywords: Modified polyimide, dielectric properties, thermal expansion coefficient.

[1] Zhang H., et al., Intrinsically Low Dielectric Constant and Low Dielectric Loss Polyimides Enabled by Rigid-Soft Structure, Chinese J. Polym. Sci. 2025, s10118-025-3338-2.
[2] Yuan H., et al., Polyimides with Ultra-Low Coefficient of Thermal Expansion Enabled by D – π – A Structure, ACS Appl. Polym. Mater. 2025, acsapm.5c00277.