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Reflection-enhanced gain in traveling-wave parametric amplifiers and plasma oscillation phase matching

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Traveling-Wave Parametric Amplifiers (TWPAs) are essential tools for ultra-sensitive measurements, particularly in quantum systems. Their performance, however, is often limited by challenges in impedance and phase matching. Conventional phase-matching techniques, such as periodic impedance modulation or the use of resonators and phase shifters, complicate circuit design and increase impedance mismatch. We show that reflections caused by such mismatches significantly alter both gain and phase-matching conditions in TWPAs [1]. To capture this behavior, we extend standard coupled-mode theory, which typically assumes only forward-propagating waves, by including reflected waves. This leads to a corrected gain formula that more accurately reflects real device performance. To overcome these limitations, we propose a simpler and more integrated solution: leveraging tunable dispersion in a Josephson junction array waveguide [2]. The desired dispersion is engineered through a metamaterial structure, achieved by periodically adding a parallel capacitor to every n-th Josephson junction. This design enables efficient phase matching in the three-wave mixing regime. Our analytical framework is supported by numerical simulations that account for the complex nonlinear dynamics present in realistic devices

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