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Dynamical evolution in gate-tunable graphene frequency combs

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Abstract: Optical frequency combs are cornerstones in modern day frequency metrology, precision spectroscopy, astronomical observations, ultrafast optics, and quantum information. Based on the Kerr and Raman nonlinearities in monolithic ultrahigh-Q microresonators, chip-scale frequency combs have recently been examined, advancing studies in optical clockwork and observations of temporal cavity solitons. The intracavity dispersion, which determines the comb formation, is however hardly amenable to electric-field tunability – whether in microcavities or fiber cavities. Arising from its exceptional Fermi-Dirac tunability and ultrafast carrier mobility, graphene has a complex dispersion determined by its gate-tunable optical conductivity. It has brought about a variety of optoelectronic advances, ranging from modulators, photodetectors to controllable plasmonics. Here, combining the cross-disciplinary field of Dirac fermions in two-dimensional graphene, we show for the first time the gated intracavity-tunability of graphene-based optical frequency combs, by coupling the gate-tunable optical conductivity onto a photonic microresonator, thus modulating its second- and higher-order dispersions through the Fermi level. Preserving cavity quality factors up to 10^6 in the graphene-based comb, we implement a dual-layer ion-gel-gated transistor to tune the Fermi level of graphene up to 0.65 eV, under single-volt-level control. We uncover the formation of charge-tunable primary comb lines from 2.3 THz to 7.2 THz, coherent Kerr frequency combs, controllable Cherenkov radiation, and controllable soliton states – all in a single microcavity. We further demonstrate the voltage-tunable transitions from periodic soliton crystals to crystals with defects, mapped by our ultrafast second-harmonic optical autocorrelation. This heterogeneous graphene-microcavity provides a new fundamental platform for the understanding of dynamical frequency combs and ultrafast optics at the interface of single atomic layer nanoscience and ultrafast optoelectronics.