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"The unreasonable effectiveness of mathematics" in evading polaritonic losses

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Polaritonic losses, a root impediment to the many bounties of nanophotonics, may be evaded by resorting to the mathematics of synthetic frequencies offering 'virtual' gain.

Polaritonic virtues are appealing, yet their inherent losses are appalling. This is a common refrain of numerous works exploring the many aspects of polaritons. Polaritons are quantum mechanical superpositions of photons with resonant collective modes in polarizable materials; examples include plasmons, phonons, magnons and excitons. Polaritons can be viewed either as excitations of a medium coupled by electromagnetic forces or equivalently as photons that are dressed by interaction with the medium. As such, polaritons are dressed quasiparticles that exhibit both light-like wave propagation and matter-like strong interactions. Their wave properties are captured in the frequency–momentum (ω, q) dispersion, which can extend to high momenta $q \gg \omega/c$ (Fig. 1a), where c is the velocity of light, so that the corresponding polaritonic wavelength $\lambda_p = 2\pi/q$ can be much shorter than the photonic wavelength $\lambda_0 = 2\pi c/\omega$. In layered van der Waals materials, including graphene, boron nitride and MoO_3, λ_p can be confined to a few tens of nanometres. The potential applications of polaritonic nanolight include super-resolution imaging, advanced chemical sensing and directional heat transport, for example. These quasiparticles also give rise to new physics, with Bose–Einstein condensation of polaritons being a spectacular example. But wait, there are losses. Ohmic losses are ingrained in the scenario of a photon dressed in a material excitation as in Fig. 1a. Unfortunately, losses reduce the highest attainable wavevectors, limit the resolution of polaritonic imaging and restrict the propagation range of polaritonic waves (Fig. 1c, top), prompting the search for loss-mitigating solutions.

One way to counteract the losses is to introduce an optical gain. However, this physics-based solution requires challenging materials engineering. Reporting in *Nature Materials*, Fuxin Guan and colleagues[1] instead turned to the mathematics of pulse shaping to obtain a 'virtual' gain[2–4]. The outcomes of the virtual gain protocol are remarkable. The phonon polaritonic fringes in MoO_3 generated using the complex frequency post-processing appear to extend their range over markedly

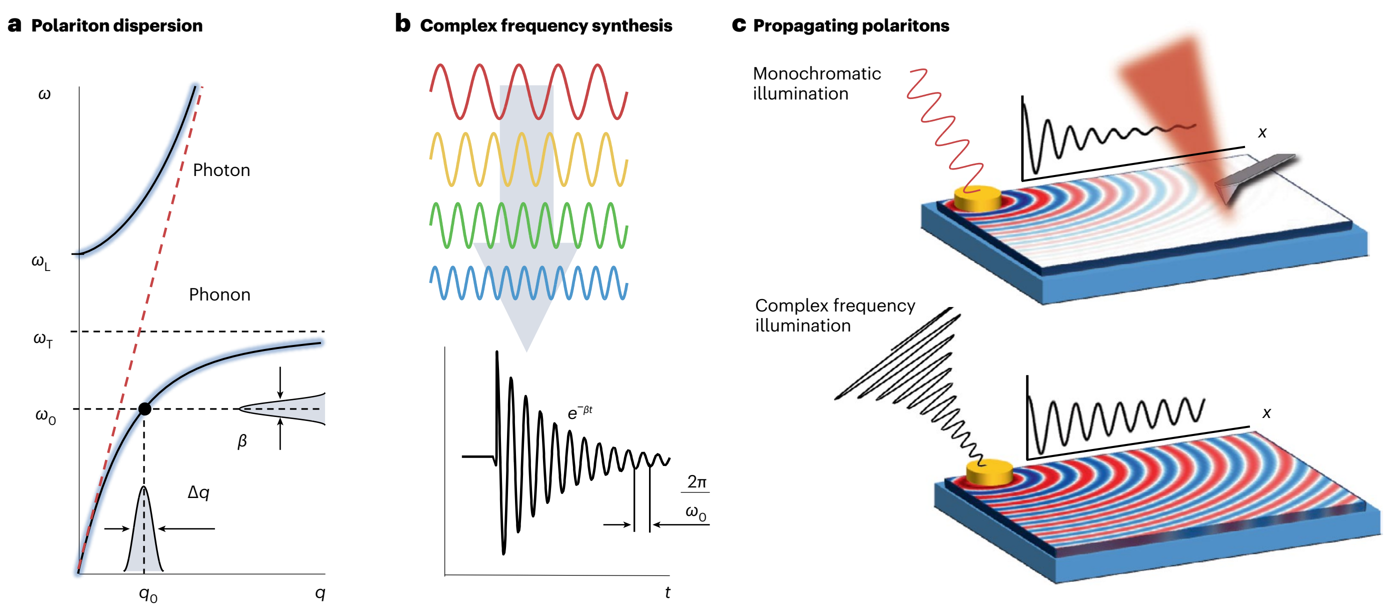

Fig. 1 | Polaritons, synthetic frequencies and their benefits. a, The coupling of a photon and a dipole-active resonance is exemplified for an infrared active phonon and leads to the characteristic mode repulsion and energy partitioning into two branches of the frequency–momentum (ω, q) dispersion. A polaritonic gap is formed between transverse and longitudinal optical frequencies ω_T and ω_L. **b**, Complex frequency waves can be synthesized from monochromatic waves (depicted as red, yellow, green and blue waves). The complex frequency wave is necessarily attenuated in time (t), a condition enforced by causality[2,3]. **c**, Polaritonic waves emanating from a circular launcher. Insets schematically display the line cuts through polaritonic waves propagating along the x axis. Even in the absence of Ohmic dissipation, polaritonic fringes emanating from a circular launcher decay because of the geometric loss. The top and bottom panels represent polariton propagation under monochromatic and complex frequency illumination, respectively.

longer distances. To borrow Eugene Wigner's line, "the unreasonable effectiveness of mathematics"[5] appears to be on display once again when applied to the problem of polaritonic loss.

Consider a Lorentzian expression for the complex dielectric function offering an adequate description of optical processes in solids, including polaritonic dispersions:

$$\varepsilon_1(\omega) + i\varepsilon_2(\omega) = 1 - \frac{F}{\Omega^2 - \omega^2 - i\omega\Gamma}. \quad (1)$$

Here, F is the oscillator strength and the Γ term codifies the spectral broadening of the material resonance at frequency Ω: the Ohmic loss. With the exception of the superfluid response in a superconductor, any other material excitation yields a finite Γ width governed by a combination of intrinsic and extrinsic factors. Even though the Ohmic loss in equation (1) is non-negotiable, this very same equation admits a potentially redeeming substitution. By resorting to the complex frequency wave $\omega \to \omega = \omega_0 - i\Gamma/2$, the imaginary part of the dielectric function (standing for the Ohmic dissipation) is eliminated once and for all. The precise choice of the complex wave in the case of polaritonic propagation $\omega = \omega_0 - i\beta$ is more nuanced as described by Guan and colleagues, because the requisite decay parameter β depends on the central frequency ω_0 but is generally of the order of the linewidth of the resonance mode in equation (1). Guan and colleagues[1], following protocols proposed in ref. 4, emulated the polariton excitation with the complex field $\omega_0 - i\beta$ constructed from a linear combination of multiple real frequencies (Fig. 1b). Their procedure yields an enhanced polariton propagation as schematically displayed in Fig. 1c.

It is safe to predict that the advantages of complex waves in polaritonic imaging[1,4] will be further explored and exploited. One task for future work is to ascertain the limits of complex wave processing. For example, if losses are so strong that polaritons are overdamped, it seems unlikely that fringe patterns can be revived by mathematics alone. We also remark that, in practice, complex frequency images are collected from dozens of separate monochromatic experiments. Thus, synthetic images benefit from improved signal-to-noise ratio obtained in prolonged data acquisition. It would be interesting to investigate if the same benefits can be gained by replacing mathematically emulated complex frequency pulses in Fig. 1b,c with the actual broadband illumination. Notably, broadband pulses are routinely produced via difference-frequency generation methods. Polariton imaging using difference-frequency generation beamlines was first demonstrated in ref. 6 and commonly used thereafter. These and other extensions of the approach of refs. 1,4 could unlock the world of polaritonic opportunities.

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Competing interests

The authors declare no competing interests.