Comment on "Spaser Action, Loss Compensation, and Stability in Plasmonic Systems with Gain"

In a recent Letter [1] Stockman studies, in quasistatic approximation (QSA), threshold conditions for lasing and loss compensation in active metamaterials and finds that they exactly coincide. This leads him to assert that only nanolasing (spasing) but not net amplification is possible in plasmonic metamaterials, a conclusion which contradicts a series of recent experimental [2] and theoretical [3–5] works. We show that the QSA approach taken in [1] is inherently unsuitable for a comparative study of these thresholds due to the *a priori* neglect of radiation, and that the theory of [1] is not applicable to realistic optical metamaterials.

In any gain system the lasing threshold is reached when both dissipative and radiative losses are compensated, whereas net amplification is achieved when only dissipative losses are overcome. Thus, the two thresholds coincide in the absence of radiative damping. For conventional lasers, for example, the lasing threshold is $R_1 R_2 \exp(2i\beta L + 2gL) = 1$ [6]. Assuming perfect mirrors ($R_1 = R_2 = 1$, absence of radiative damping), this relation indeed reduces to the threshold condition of an amplifier: the small-signal gain g equals the imaginary part of the propagation constant β (internal loss). In [1], despite the assumption of a bright mode, the threshold conditions for amplification and spasing [Eqs. (9) and (13)] are formulated in QSA, completely neglecting radiative damping. Therefore, as radiative loss marks the difference between lasing and amplification thresholds, both conditions therein trivially coincide.

The presence of inherently significant radiative damping in practical (transmissive) optical metamaterials [7] leads to an also significant separation between the loss compensation and lasing thresholds. For the case of an optically pumped, active fishnet metamaterial this is demonstrated in Fig. 1: At a dye density $N_0 = 1.2 \times 10^{19}$ cm^{-3} (sufficient for loss compensation [3]) we find that the electric far-field amplitude decays exponentially after a probe pulse passes through the structure [Fig. 1(a)]. By contrast, for a dye density $N_1 = 2N_0$ we see in (a) that there is a rapid exponential increase of the far-field at around 200 fs (indicating the onset of a lasing instability), followed at around 1500 fs by a more intense (by a factor $\approx 10^3$) lasing burst [Fig. 1(b)]. As expected [6], only the lasing burst is associated with appreciable gain depletion [Fig. 1(b)]. Thus, here the amplification and lasing thresholds clearly do not coincide, opening a window for net amplification.

These results also show that the statement in [1] that an "equation for coherent SP amplitude is absent" in the MB theory of [3], implying that neither gain depletion nor lasing instability can therein be observed, is incorrect. All the coherent effects are self-consistently included in an MB analysis [7,8] and, based on it, active metamaterials can be modeled both in the amplifying and lasing regimes.

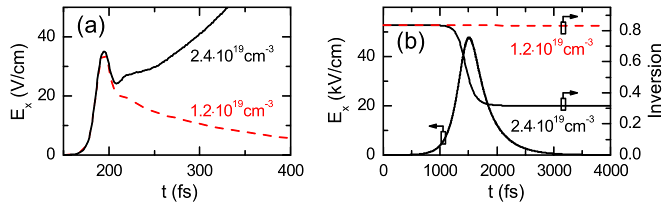

FIG. 1 (color online). (a) Electric far-field amplitude E_x for gain densities $N_0 = 1.2 \times 10^{19}$ cm^{-3} (red dashed line) and $N_1 = 2N_0$ (black line) computed on the basis of a 3D full-wave Maxwell-Bloch (MB) method [7], (b) Same as in (a) for later times together with the inversion at a position of high field enhancement.

We also note that the assumption in [1] of "a small piece of a metamaterial with sizes much greater that the unit cell but much smaller than $\lambda\!\!\!^{-}$, which is a metamaterial itself" does not apply to realistic optical metamaterials in general and to the fishnet structures considered in [1] in particular. Further, it is incorrect to consider modes of a (subwavelength) piece of a *dense* periodic metamaterial in isolation, since the fields in adjacent pieces couple either evanescently via dipole-dipole coupling [9] or radiatively. The modes of these materials are therefore defined over the whole structure and, if bright, couple at the boundaries of the finite structure to the radiative continuum. Thus, the assumptions made in [1] may justify the QSA but do not generally hold true for optical metamaterials.

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Received 13 May 2011; published 13 December 2011
DOI: 10.1103/PhysRevLett.107.259701
PACS numbers: 73.20.Mf, 42.50.Nn, 78.67.Pt, 81.05.Xj

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