Nonlinear optics in waveguides doped with dimers of metal nanoparticles

A. D. Sánchez, N. Linale and D. F. Grosz
Depto. de Ingeniería en Telecomunicaciones, Centro Atómico Bariloche, Comisión Nacional de Energía Atómica, Río Negro 8400, Argentina
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina

P. I. Fierens
Grupo de Optoelectrónica, Instituto Tecnológico de Buenos Aires (ITBA), CABA 1106, Argentina
Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina

Abstract: We investigate the nonlinear response of waveguides doped with dimers of noble-metal nanoparticles using a simple effective model. Our results show a markedly distinctive response depending on the dimer gap. © 2020 The Author(s)

1. Summary

It is well known that waveguides doped with metal nanoparticles (MNPs) exhibit nonlinear coefficients several orders of magnitude larger than, i.e., that of fused silica [1]. Moreover, since plasmonic responses are in the femtosecond timescale, there is a great interest in the potential application of this type of waveguides to ultrafast devices in optical systems [2]. In this work we focus on the properties of waveguides doped with dimers. Our study involves two parts. First, we characterize the nonlinear coefficients of such waveguides by introducing a novel effective approach based on approximating the behavior of a dimer by that of an equivalent single-particle inclusion. Then, we explore nonlinear propagation in these waveguides. In particular, we look at the modulation instability (MI) phenomenon, which is of special interest in a wide range of applications in nonlinear photonics [3]. Since the nonlinear parameter in MNP-doped waveguides is highly frequency-dependent, we do not resort to the usual nonlinear Schrödinger equation to model propagation, as it is known that it leads to unphysical results in this case. Instead, we turn to the recently introduced photon-conserving nonlinear Schrödinger equation (pcNLSE), which has been shown to produce consistent results for arbitrary frequency-dependent nonlinear coefficients [4,5].

Modeling nonlinearities in waveguides with inclusions of dimer MNPs can be quite involved [6]. In this work we introduce a simple approach that approximates the behavior of a dimer by that of a single effective particle. Specifically, the size of the effective MNP is adjusted so that it reproduces the intensity of the electric field in the so-called 'hot spot' of the dimer, i.e., the gap between the two nanoparticles (see Fig. 1).

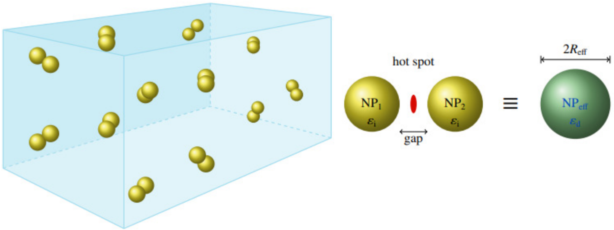

Fig. 1. (Left) Schematic of the doped waveguide. (Right) The dimer and the effective MNP. The field intensity of the single MNP equals that in the gap of the dimer.

Once the single-nanoparticle approximation is introduced, we use the Maxwell Garnett (MG) model to find an expression for the waveguide effective third-order susceptibility (TOS) [7]

$$\chi_{\mathrm{eff}}^{(3)} = \chi_{\mathrm{i}}^{(3)} p\, |f|^2 f^2, \tag{1}$$

where $\chi_{\mathrm{i}}^{(3)}$ is the TOS of the inclusion, p the filling factor, and f is the local-field enhancement factor of the single MNP. Using Eq. 1 and the effective electric permeability predicted by the MG theory, we compute the nonlinear refractive index and the nonlinear parameter of the waveguide using the standard definitions [8].

In order to study the modulation instability phenomenon in such waveguides, we resort to the pcNLSE. Analytical expressions for the MI gain under this equation can be found in Ref. [9]. Figure 2 shows both the MI gain profile (top) and the simulated amplification of noise under a strong pump (bottom), for both Ag- and Au-dimers, and for two different gaps. As it can be observed, quite different MI-gain profiles can be obtained by adjusting the gap between the particles. In the case of Ag-dimers, the number of amplification bands changes with the gap. For Au-dimers, a change in the bandwidth of the MI-gain is observed as the gap is varied.

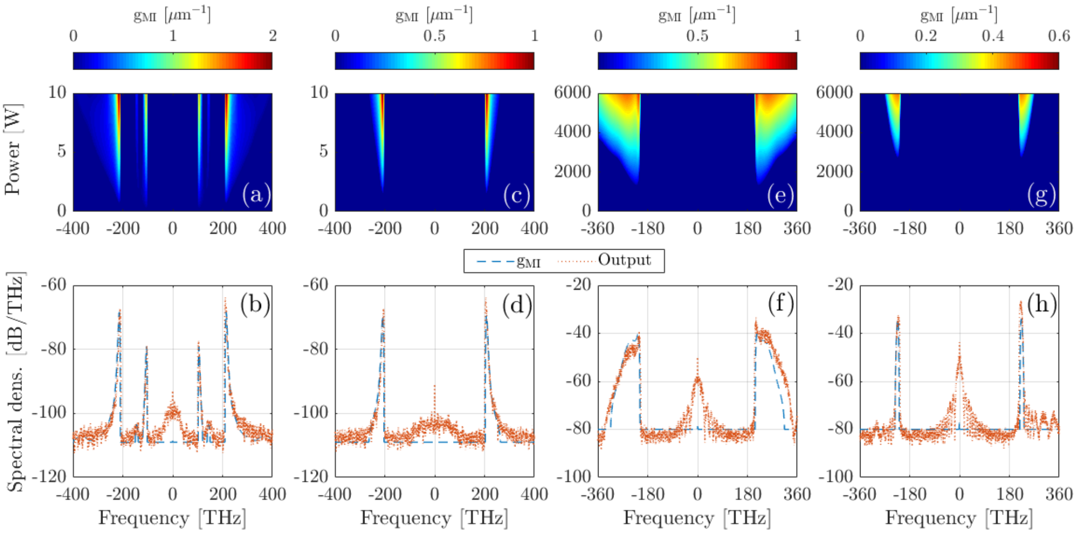

Fig. 2. MI-gain profiles (top panels) and light propagation in the waveguide (bottom panels) for dimers with 20-nm diameter single NPs. Ag-dimers with 2-nm gap (a-b) and 10-nm (c-d), both with a 10-W pump power at 532 nm, along 4.9 and 10 µm, respectively. Au-dimers with 2-nm (e-f) and 10-nm gap (g-h), both with a 3000-W pump power at 800 nm, along 27.5 and 98 µm, respectively. The host medium is silica and the GVD parameter is $\beta_2 = -100$ ps^2/km in all cases.

To summarize, we introduced a simple single-particle effective model for MNP dimers and used it to obtain the nonlinear response of a doped waveguide. Markedly distinct MI-gain spectra are shown to be attainable through engineering of the gap. These findings are of relevance in the area of integrated photonic devices.

References

1. J. Olesiak-Banska, M. Gordel, R. Kolkowski, K. Matczyszyn, and M. Samoc, “Third-order nonlinear optical properties of colloidal gold nanorods,” The Journal of Physical Chemistry C **116**, 13731–13737 (2012).
2. T. K. Liang, L. R. Nunes, T. Sakamoto, K. Sasagawa, T. Kawanishi, M. Tsuchiya, G. R. A. Priem, D. Van Thourhout, P. Dumon, Pieter and R. Baets, and H.K. Tsang, “Ultrafast all-optical switching by cross-absorption modulation in silicon wire waveguides,” Optics Express. **13**, 7298–7303 (2005).
3. T. J. Kippenberg, R. Holzwarth, S. A. Diddams, “Microresonator-based optical frequency combs,” Science **332**, 555–559 (2011).
4. J. Bonetti, N. Linale, A. D. Sánchez, S. M. Hernandez, P. I. Fierens, and D. F. Grosz, “Modified nonlinear Schrödinger equation for frequency-dependent nonlinear profiles of arbitrary sign,” J. Opt. Soc. Am. B **36**, 3139–3144 (2019).
5. A. D. Sánchez, N. Linale, J. Bonetti, and D. F. Grosz, “Modulation instability in waveguides doped with anisotropic nanoparticles,” Opt. Lett. **45**, 3119–3122 (2020).
6. J. Khurgin and G. Sun, “Third-order nonlinear plasmonic materials:Enhancement and limitations,” Phys. Rev. A **88**, 053838 (2013).
7. X. Zeng, D. Bergman, P. Hui, and D. Stroud, “Effective-medium theory for weakly nonlinear composites,” Phys. Rev. B **38**, 10970 (1988).
8. G. P. Agrawal, *Nonlinear Fiber Optics* (Springer, 2000).
9. N. Linale, J. Bonetti, A. D. Sánchez, S. Hernandez, P. I. Fierens, and D. F. Grosz, “Modulation instability in waveguides with an arbitrary frequency-dependent nonlinear coefficient,” Opt. Lett. **45**, 2498–2501 (2020).