An Approach to Realizing Index Enhancement without Absorption for Immersion Lithography

V. Anant, M. Rådmark, T.C. Killian, K.K. Berggren
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In this work, we propose and evaluate a scheme for refractive index enhancement that achieves the following objectives: (1) an index of refraction greater than unity in an atomic vapor; and (2) optical amplification rather than absorption of the propagating probe beam. The scheme achieves the first of these objectives by tuning the probe beam close to an atomic resonance. The second is achieved by using an additional incoherent optical pump beam that inverts population between the two levels with which the near-resonant probe beam interacts. This scheme is simple and is shown to be tolerant to temperature-related broadening effects. However, it is susceptible to intensity-related broadening effects and background noise, due to amplified spontaneous emission. Such a scheme may find applications in the fields of immersion microscopy and immersion photolithography, where the high-index material could replace lower-index immersion liquids, as well as in applications such as all-optical switching, where an optically controlled refractive index is desirable.

Figure 1: Energy level diagram showing incoherent decay rates and driving fields for the index-enhanced medium. A two-level system with ground state |\( b \rangle \) and excited state |\( c \rangle \) interacts with a coherent oscillating electromagnetic probe field at frequency \( \nu \) detuned by \( \Delta \) from the energy difference \( \omega_{cb} \) between |\( b \rangle \) and |\( c \rangle \). An incoherent oscillating electromagnetic pump field at frequency \( \omega_{ab} = \omega_{cb} \) promotes population from |\( b \rangle \) to upper lying level |\( a \rangle \). |\( a \rangle \) is an upper level that decays at rate \( \Gamma_{ac} \) to level |\( c \rangle \).

Figure 2: Plot of the refractive index \( n'' \) and absorption coefficient \( n'' \) as a function of \( \Delta \) for the 4'S, to 4'P, transition in Ca: (a) pumped case, and (b) un-pumped case. For the pumped case, we see that \( n'' < 0 \), resulting in amplification (rather than absorption) of the probe laser. The maximum value of \( n'' \) occurs slightly off resonance (\( n_{\text{max}} \approx 6 \) at \( \Delta \approx 0.3 \Gamma_{cb} \)).