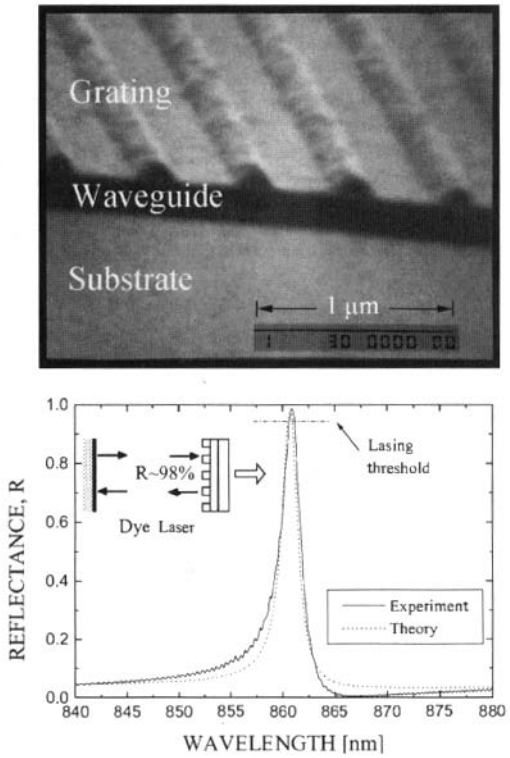
tions of the externally propagating fields at certain values of the wavelength and angle of incidence that allows coupling of the incident beam to a leaky mode of the waveguide.[3, 4] With appropriate choice of materials and geometrical parameters, this (GMR) effect can be exploited to design polarized, narrowband reflection filters with efficiencies approaching 100%.[4, 5]

The GMR mirror is fabricated by depositing a layer of HfO$_2$ on a fused-silica substrate with subsequent recording of a holographic grating in photoresist on top of the HfO$_2$ layer. This structure is shown in the SEM of Figure 1, which further illustrates the spectral response of this two-layer GMR filter for a normally incident TE-polarized probing beam. The filter exhibits a peak reflectance of 98% at ~860 nm with a FWHM-linewidth of ~2.2 nm and low sidebands (< 5%) over the wavelength range provided by the dye. The experimental curves and the theoretical calculations agree well (see Fig. 1).

The high-efficiency GMR reflection filter described above is used to realize a GMR laser mirror. The flat output mirror of a dye laser with broadband output (800–920 nm) is replaced with the GMR filter and the birefringent tuning element removed. Lasing is achieved at a wavelength of ~860 nm. The laser power is ~100 mW when pumped with an argon laser emitting a power of ~5 W at a 514-nm wavelength. The linewidth of the output laser beam is measured as ~0.3 nm. This linewidth is set by the GMR filter linewidth at the threshold reflectance for laser oscillation to occur; in this case at ~95% reflectance value, as indicated in Figure 1.

In conclusion, a GMR laser mirror with efficiency approaching the theoretical limit has been presented. The mirror characteristics define the laser's output polarization, wavelength, and linewidth.



Magnusson Figure 1. Spectral response of the GMR laser mirror with the device structure illustrated in the SEM.

Acknowledgments

This work was partly supported by the Texas Advanced Research Program under grant 003656-071 and by NSF under grant ECS-9512504.

References

1. Z.S. Liu *et al.*, "High-efficiency guided-mode resonance filter," Opt. Lett. **23**, 1556 (1998).
2. I.A. Avrutsky and V.A. Sychugov, "Reflection of a beam of finite size from a corrugated waveguide," J. Mod. Opt. **36**, 1527 (1989).
3. R. Magnusson and S.S. Wang, "New principle for optical filters," Appl. Phys. Lett. **61**, 1022 (1992).
4. S.S. Wang and R. Magnusson, "Design of waveguide-grating filters with symmetrical line shapes and low sidebands," Opt. Lett. 19, 919 (1994).
5. S.S. Wang and R. Magnusson, "Multilayer waveguide-grating filters," Appl. Opt. **34**, 2414 (1995).

Surface-mode-induced Rescaling of the Dipole-dipole Interaction

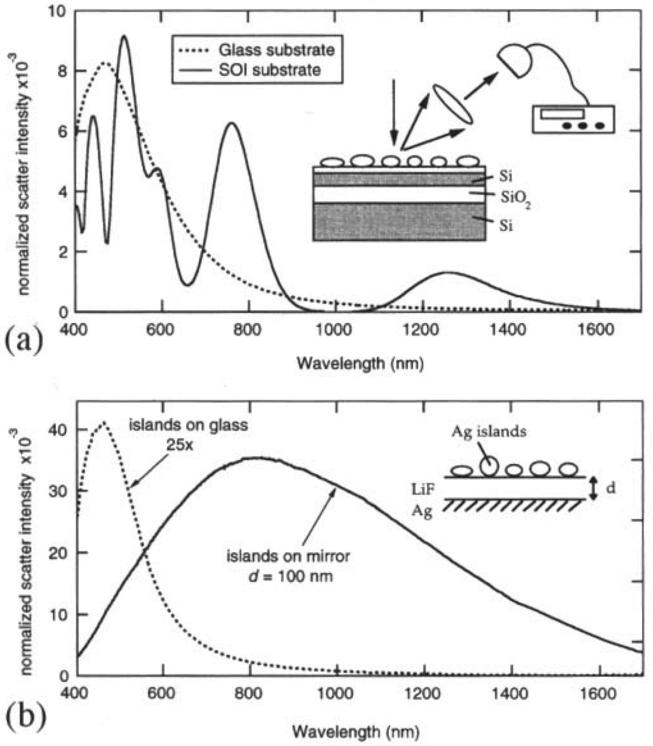
Howard R. Stuart and Dennis G. Hall, The Institute of Optics, Univ. of Rochester, Rochester, NY.

A surface or structure can modify the optical properties of a nearby radiator. These effects include the modification of a molecule's radiative lifetime near a metal surface[1] and the strikingly large effect known as surface-enhanced Raman scattering (SERS).[2] During our attempts to understand the mechanism responsible for another dipole-surface effect—nanoparticle-enhanced photodetection[3]—we found evidence that a nearby surface can also modify the dipole-dipole interactions taking place within a layer of radiators, producing rather dramatic results.[4]

In nanoparticle-enhanced photodetection, a silver-island film placed near a thin silicon-on-insulator (SOI) photodetector increases by nearly a factor of 20 the photocurrent produced by normally incident light.[4] Surprisingly, peak enhancement occurs near $\lambda = 800$ nm, far from the resonance wavelength of the island film. This suggests the thin (160 nm) silicon underlayer modifies the resonance in a significant way.

We probed the character of the resonances using elastic light-scattering (see Fig. 1a, inset). Light from a tungsten-halogen lamp passes through a monochromator before illuminating each sample at normal incidence. An optical system collects and detects diffusely scattered light over a broad angular range (~$2\pi/5$ steradians, centered at 45° off-normal). The dotted curve in Figure 1a shows the scattering spectrum of a silver-island film (mean particle diameter ~100 nm) on a glass substrate. The broad peak near 470 nm, the "bare" resonance, is due to radiative plasma resonances supported by the nanoparticles that make up the island film. The solid curve in Figure 1a shows the scattering spectrum of a similar silver-island film placed 30 nm above the SOI photodetector. The compound island-SOI resonance is qualitatively different, containing prominent features near 800 and 1300 nm, wavelengths at which the bare resonance is either quite weak or negligible.

The dramatic changes evident in Figure 1a occur because light scattered by the island layer is strongly coupled into waveguide modes supported by the SOI structure. These modes provide a new channel for energy transport among the particle-dipoles, rescaling the dipole-dipole interaction between nanoparticles. The waveguide-mediated interaction proceeds as $e^{-\alpha r}/(r)^{1/2}$, where r is the separation distance and α depends on the propagation length of the mode. Our preliminary modeling indicates that each peak in the scattering spectrum can be associated with the optimal coupling range of a particular guided mode. Measurements made using other types of substrates (silver mirrors) produce equally dramatic results that support this interpretation (see Fig. 1b).



Stuart Figure 1. (a) The measured intensity of scattered light (normalized to the incident intensity) for a Ag-island film formed on LiF-coated glass (dotted line) and SOI (solid line). LiF thickness is 30 nm. The experimental geometry is shown in the inset. (b) Identical measurement for a Ag-island film formed on a LiF-coated silver mirror. The islands-on-glass curve is expanded by 25x. The single broad peak in the islands-on-mirror curve is due to the single-mode supported by the silver surface (the surface plasmon).

This novel energy-transfer process represents a new dimension to the dipole-surface problem with several potential applications (enhanced photodetection being one example). Plasma resonances supported by metal nanoparticles are known to produce important optical effects (such as SERS), due to strongly-enhanced local electromagnetic fields. The peaks seen in the figure are likely associated with enhanced local fields occurring at the new resonances of the composite particle-waveguide system. These structures may be capable of enhancing multifrequency nonlinear effects (such as second-harmonic generation) to a degree exceeding previous observations by several orders of magnitude.

Acknowledgments

This research was supported by the U.S. Army Research Office. Howard Stuart acknowledges the support of the Fannie and John Hertz Foundation. Thanks to Subramanian Iyer (SiBond LLC) for providing the SOI wafers.

References

1. K.H. Drexhage, "Interaction of Light With Monomolecular Dye Layers," *Progress in Optics,* E. Wolf, ed. **12** (North-Holland, Amsterdam, 1974), pp. 163–232.
2. M. Moskovits, "Surface-enhanced spectroscopy," Rev. Mod. Phys. **57,** 783–826 (1985).
3. H.R. Stuart and D.G. Hall, "Absorption enhancement in silicon-on-insulator waveguides using metal island films," Appl. Phys. Lett. **69,** 2327–2329 (1996).
4. H.R. Stuart and D.G. Hall, "Enhanced dipole-dipole interaction between elementary radiators near a surface," Phys. Rev. Lett. **80,** 5663–5666 (1998).

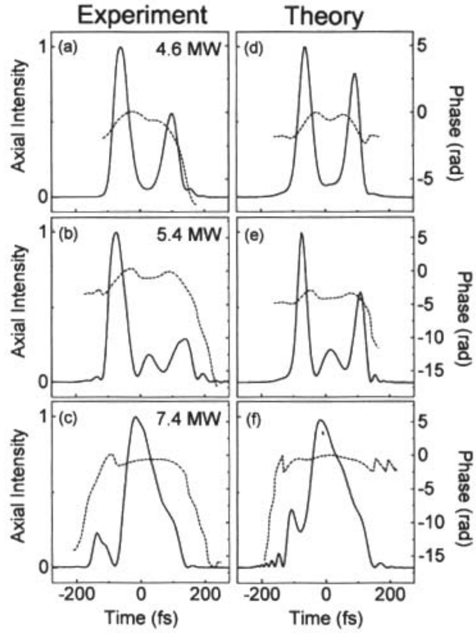
PROPAGATION

Unraveling the Mysteries of Intense Femtosecond Pulse Propagation

Scott A. Diddams, Hilary K. Eaton, Amelia G. Van Engen, and Tracy S. Clement, JILA, Univ. of Colorado, and NIST, Boulder, CO; Alex A. Zozulya, Dept. of Physics, Worcester Polytechnical Institute, Worcester, MA.

Propagation of electromagnetic pulses is of fundamental importance in pure and applied science, and the recent development of sources of intense femtosecond laser pulses has added many interesting twists to this long-standing problem. The broad spectral bandwidths, high peak powers, and 4-D nature of femtosecond fields give rise to complicated linear and nonlinear dynamics that have posed significant challenges to researchers. A few years ago, it was observed that in contrast to a continuous beam of light, a femtosecond pulse having the same peak power does not collapse to a singularity under the influence of self-focusing in a nonlinear medium.[1, 2] Instead, the original pulse splits temporally into two pulses of lower power.[2] However, the details of this splitting process remained unclear, and furthermore, it was unknown whether the newly split pulses would in turn undergo a secondary splitting.

In the past year, we have applied the new technique of frequency-resolved optical gating (FROG) to this problem.[3, 4] The FROG measurement gives detailed data on both the amplitude and the phase of the pulse, as opposed to the indirect techniques of auto- and cross-correlations. As such, FROG presents a unique opportunity of directly "seeing" the shape of a pulse on a femtosecond time scale and enables more quantitative comparison of theory and experiment. Based on our new experimental results, we offer a detailed scenario of the spatio-temporal evolution of femtosecond pulses in nonlinear media with normal group velocity dispersion. We find that the sequence of events at progressively higher powers can be characterized by a single splitting, then multiple splittings, and finally a coalescence of the pulses. This is shown in Figure 1, where both FROG measurements (left column) and numerical simulations (right column) are presented for three different peak powers. The measurements of the



Diddams Figure 1. (a–c) Measured intensity (black solid line) and phase (dashed line) of an intense femtosecond pulse after passing through 3 cm of fused silica. The input peak powers for fields of plots (a–c) are 4.6, 5.4, and 7.4 MW. Plots (d–f) show the corresponding numerical calculations.