Regular article

Plasmonic infrared-laser attenuator

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ABSTRACT

We describe two designs for a variable attenuator of infrared laser radiation. The principle is based on the excitation of surface plasmon polaritons with prism couplers on suitable conductors. Practical considerations dictate the use of conductors with infrared plasma frequency. An intensity variation of more than nine-orders is theoretically demonstrated. Both designs involve mechanical displacements of optical elements by less than several microns, which in principle might be much faster than current art for variable attenuators of IR laser beams. One design provides fine control at high attenuation. Experimental demonstrations support the predicted function.

1. Introduction

Fast amplitude modulation of infrared laser intensity has applications to (e.g.) telemetry and laser machining. A number of variable attenuators for IR lasers are known, including partially-absorbing materials of variable thickness [1], diffractive metal screens [2], wire grids [3], pinholes [4], variable-angle etalons [5], and rotating Brewster-angle polarizers [6]. None of these allow rapid variation of attenuation and the range of attenuation is typically less than three or more orders of magnitude. Some additional approaches to infrared laser attenuation, each with its own advantages and disadvantages, are described in the discussion section.

We propose two designs for an attenuator of polarized infrared laser beams based on absorption due to excitation of surface plasmon polaritons (SPP) on a conductor. We demonstrate the practical importance of using a conductor with infrared plasma frequency. One of the designs features fine control at high attenuation. Variable extinction by up to 9 orders of magnitude is predicted. Attenuation is determined by mechanical actuation over just micron distances, which in principle could be fast. Experiments demonstrate the operation principle and support the accuracy of the calculations.

SPPs are bound electromagnetic waves at the interface of a dielectric and conductor. SPP fields are coupled to surface-charge oscillations. Optical excitation of SPPs requires slowing the incident free-space beam to match the SPP momentum. Such excitation of an SPP can be achieved using a prism at an internal angle-of-incidence beyond that for total internal reflection (TIR), such that the in-plane wavevector of the associated external evanescent wave equals the SPP wavevector.

An SPP prism coupler separated from a smooth conducting surface by the TIR evanescent wave’s characteristic exponential decay length compromises the Otto configuration [7]. Alternatively, a semi-transparent conducting film applied directly to the prism surface comprises an SPP coupler in the Kretschmann configuration [8]. Hybrid couplers are also known [9].

SPP excitation removes energy from the excitation beam, a resonant phenomenon in frequency and angle. For a given incidence angle above TIR within the prism, SPP creation appears as a dip in reflectance plotted vs wavelength. Similarly, for a given wavelength, SPP creation appears as a dip in reflectance plotted as a function of angles above TIR. The energy lost from the excitation beam is converted to heat via SPP propagation losses. The resonant attenuation depends on the air gap for Otto configuration, metal thickness for Kretschmann, and permittivity spectra of all materials. Attenuation is maximized for monochromatic, collimated, and p-polarized excitation beams, e.g. for lasers.

Fig. 1 (left) presents an attenuator design based on the Otto-configuration [7,10]. Transverse-magnetic (TM) (p-polarized) light, indicated by the thick arrows, is incident at the SPP resonance excitation angle \( \theta_{SPP} > \theta_{TIR} \). SPPs are excited on the conductor surface that is separated from the prism by the air gap of dimension \( d \). The SPPs propagate to the right as indicated and decay into heat. Their fields are...
exponentially damped away from the conductor surface, as suggested in Fig. 1. If \( d \) is much larger than the TIR evanescent wave decay length, no SPP is excited, and reflectance \( R \) is unity. Similarly, it is obvious that as \( d \) goes to zero, \( R \) again approaches unity. There is an optimum \( d \) that maximizes the attenuation, which can be varied by changing \( d \). A positive feature of the Otto coupler is that the conductor can be thermally designed to safely absorb high average laser powers by removing heat from the backside. A negative feature of the Otto coupler is that it may be difficult in practice to achieve the maximum predicted attenuation because of the precision required for the value of \( d \). That consideration motivates the hybrid coupler discussed next.

Fig. 1 (right) presents an attenuator design based on a hybrid Otto-Kretschman coupler. A semi-transparent film of conductor 1 is deposited directly on the prism surface. Conductor 2 is separated by a distance \( d \). The SPP propagates on the interface between conductor 1 and air, and the SPP fields decay exponentially away from this interface. If \( d \) exceeds that exponential decay length, then the resonance attenuation has its maximum possible value, independent of the precise value of \( d \). As \( d \) goes to zero, reflectance approaches unity. At intermediate distances, the excited SPP is shared between the two conductor surfaces [9], hence the name “hybrid”. An advantage over the Otto coupler is that precise air gap control is unnecessary to minimize reflectance, facilitating on-off modulation. Also fine control of high attenuation is possible. Power handling capability would depend on the ability of the prism to dissipate the heat generated in conductor 1.

In this work, Otto- and hybrid-coupler design calculations were made for the infrared, considering different conductors. Finally, we present experimental demonstrations.

2. Theoretical considerations

Considering the dielectric to be air, the momentum-matching condition for exciting SPPs with either of the Fig. 1 couplers is

\[
n_p \sin \theta_{SPP} = \frac{\sqrt{\varepsilon_c(\omega)}}{\varepsilon_r(\omega) + 1}
\]

where \( \varepsilon_c \) is the complex frequency-dependent permittivity of the conductor and \( n_p \) the prism’s refractive index. Eq. (1) resembles the condition for total internal reflection (TIR), namely

\[
n_p \sin \theta_{TIR} = 1
\]

To support an SPP [8], the conductor should have \( \varepsilon' < 0 \) and \( |\varepsilon'| \gg \varepsilon'' > 0 \). Hence, the SPP excitation resonance is always observed at incidence angles \( \theta_{SPP} > \theta_{TIR} \). However, if \( |\varepsilon'| \) is too large, the angles \( \theta_{SPP} \) and \( \theta_{TIR} \) are almost equal, and the resonance narrows angularly to a near delta function, which complicates alignment and collimation for optimum attenuation. Broad angular resonances occur when \( \theta_{SPP} \) significantly exceeds \( \theta_{TIR} \), which requires the smaller (negative) \( \varepsilon' \) values that occur when the operating wavelength \( \lambda \) is just beyond the conductor’s plasma wavelength \( \lambda_p \). For purposes of this work, it suffices to define the plasma wavelength as that where the real part of the permittivity passes through zero and changes sign.

The SPP fields decay exponentially away from the surface with a characteristic length \( L \) given by [8]

\[
\frac{1}{L} = \left(\frac{2\pi}{\lambda}\right) \frac{\text{Re}(-1)}{\varepsilon_r(\omega) + 1}
\]

This SPP mode height is important in the determining the useful range of \( d \) for both coupler designs.

The SPP resonance condition Eq. (1) tells nothing about the resonance strength or angular line shape. However, these are accurately calculated using the well-known analytic Fresnel equations for a multilayer system. Our calculation method and experimental validation are described in [9,10].

3. Experimental details

Otto-configuration experiments at 5.6 \( \mu \m \) wavelength were performed using a TM polarized quantum cascade laser [11], a CaF\(_2\) prism (Thorlabs), a 0-20 goniometer, and a thermopile detector (Coherent Powermax USB). The conductor for these experiments was fluorine-doped tin-oxide (F:SnO\(_2\), or “FTO”, SISOM Thin Films) on glass. Thorough characterization of these FTO films relevant to SPPs was reported in [12-14]. The plasma wavelength for FTO used here was in the range 3 to 4 \( \mu \m \).

Hybrid coupler experiments were performed using a sapphire prism coated with the transparent conducting oxide Gallium-doped Zinc Oxide (GZO) separated from an Al mirror by a thin layer of air. The GZO was deposited on the prism using an AJA three gun sputtering system and a custom prism chuck. Radiation with 4.5 \( \mu \m \) wavelength and p-polarization from a narrow band Quantum Cascade laser was collimated by an off-axis parabolic mirror. The specularly reflected beam was detected using the goniometer and a 77 K mercury cadmium telluride (MCT) detector.

4. Results

A conductor with infrared plasma wavelength [15-21] would facilitate practical implementation. Fig. 2 presents SPP resonance angles (solid red square symbols) calculated from Eq. (1) at an operating wavelength of 5.6 \( \mu \m \) for several representative materials spanning a range of plasma wavelengths. The horizontal dashed red line labeled (TIR) in Fig. 2 indicates the critical angle. All of the resonance angles are beyond the critical angle, as expected. The resonance angles increase as the plasma wavelength increases toward the operating wavelength.
Fig. 2 also presents the SPP mode height $L$ as a function of plasma wavelength for the same set of materials. A horizontal dashed line indicates the mode height that equals the 5.6 $\mu$m operating wavelength. The SPP tends to become more confined as the plasma wavelength of the conductor increases toward the operating wavelength. For gold, the $L$ value is 12 times larger than the operating wavelength. For the 5% FTO sample, $L$ is twice smaller than this wavelength. Our calculations (below) show that the SPP mode height gives roughly the gap value required for optimal Otto-coupling and maximum attenuation.

Experiments at visible wavelengths demonstrated the strong dependence of attenuation on the gap and the accuracy of the Fresnel calculations [10]. Fig. 3 presents such calculations at 5.6 micron wavelength. Fig. 3 (right) presents Fresnel-calculated IR reflectance vs. incidence angle for the same five conductors considered in Fig. 2. One sees that for Au and Mo with $\lambda_p \ll \lambda$, the resonance occurs close to the 45.6° TIR angle and such resonances are inconveniently sharp. On the other hand, as $\lambda_p$ approaches $\lambda$ in CuSnS and FTO, the resonance angular width increasingly broadens, which would facilitate optical alignment. Apparently, the minimum reflectance is independent of plasma wavelength. In other words, any conductor with $\lambda_p \ll \lambda$ can provide a “100%” deep resonance at the optimum gap $d$, but those with longer plasma wavelength would be more practical.

Fig. 3 (left) presents reflectance for the considered materials as a function of the air gap at the optimum angle of incidence for 5.6 $\mu$m operating wavelength. The horizontal axis is logarithmic in this case. When $\lambda_p \ll \lambda$, as for Au and Mo, resonances occur at gaps that exceed 10 $\mu$m and they change with the gap over $\sim 10 \mu$m scales. When $\lambda_p$ approaches $\lambda$, as for FTO, resonances occur at $d \sim 1 \mu$m, and they change significantly for gap changes of only a few microns. These smaller displacements would be much more convenient for control by a (e.g.) microelectromechanical systems (MEMS) actuator.

By comparing Fig. 3 (left) with Fig. 2, we see that coupling is optimized for maximum attenuation when $d \sim L$. For instance, the minimum reflectance for 10% FTO occurs at a gap of 3 $\mu$m in Fig. 3 (left), and the SPP mode height for this material from Fig. 2 is also 3 $\mu$m.

Fig. 4 presents measured and Fresnel-calculated angular reflectance spectra for an Otto coupler comprising CaF$_2$ prism, air gap, and FTO at 5.6 $\mu$m operating wavelength for two different air gaps. Experimental data are represented by the solid lines, which nearly coincide with the theoretical values represented by dashed lines. The air gap was varied for this demonstration by applying force between the prism and the FTO-coated substrate. The air gap values were found by matching the Fresnel-calculated resonance angle to the value determined from the reflectance experiment, because micron sized air gaps are difficult to independently measure. The achievable air-gap was several times larger than the 1.5–3 $\mu$m values indicated in Fig. 3 (left) for the strongest absorption, which explains why the experimental resonances are fairly weak. However, an important point is the evident agreement between the experiment and the Fresnel calculation, which means the latter can be used predictively. To achieve smaller gaps and stronger resonances would require very flat surfaces and assembly in a cleanroom environment to avoid any dust in the gap.

Fig. 5 presents a calculation of reflectivity vs. gap at the angle of maximum attenuation for a CaF$_2$/air/FTO Otto coupler. The two curves are the same data plotted linearly or semi-logarithmically. The linear plot shows a linear tenfold decrease in reflectivity as the gap increases from 0 to 2 $\mu$m. The reflectivity increases linearly again beyond 3.5 $\mu$m with about the same slope. Between 2 and 3.5 $\mu$m, the reflectance changes non-linearly, reaching a minimum of $2 \times 10^{-10}$ at a gap of about 2.84 $\mu$m. Thus, the attenuation can be changed by over 9 orders of magnitude, in principle, though practical considerations lower this expectation. At the highest attenuation, the curve changes very rapidly with the gap. At the minimum, the attenuation changes by 2x for a positional change of only 0.1 nm. This would pose severe difficulties for implementation and control, considering that surface roughness would likely exceed several nm [12]. However, attenuation by up to 10,000 times might be practical and controllable. The last order of magnitude change would require 50 nm displacement, which seems feasible with piezoelectric actuators. An attenuation range of 10,000 is better than obtained with usual IR attenuators [1–6]. The plasmonic device

Fig. 3. CaF$_2$-based Otto coupler reflectance at 5.6 $\mu$m operating wavelength as a function of gap at optimum angle (left) and as function of angle at optimum gap (right) for different conductors.

Fig. 4. Measured and Fresnel-calculated angular reflectance spectra for an Otto coupler comprising CaF$_2$ prism, air gap, and FTO at 5.6 $\mu$m operating wavelength.

Fig. 5. Calculated reflectance vs. gap at optimum angle for CaF$_2$/air/FTO Otto-coupler at 5.6 $\mu$m operating wavelength.
presented here has the advantage that the attenuation might be rapidly changed under electronic control.

For the hybrid coupler of Fig. 1 (right), the SPP is excited on the semitransparent conductor 1 deposited on the prism face. The absorption is strongest for large gaps, where the hybrid becomes a pure Kretschmann coupler. Calculations such as those for Figs. 2 and 3 again conclude that the angular width of the SPP resonance is inconveniently narrow for Au and similar metals. Moreover, to achieve the strongest absorption, gold as conductor 1 should thinner than 10 nm, but such is difficult to make continuous and uniform [22]. Calculations show that conductor 1 should have an infrared plasma wavelength. Since the aqueous spray method we used for FTO is unsuited for deposition on prisms, we instead used the similar conducting-oxide Gd-doped Zinc Oxide (GZO) [14], which can be deposited by pulsed-laser deposition [14] or sputtering [23]. For our calculations we choose a GZO thickness of 152 nm and a sheet resistance of 0.6 mΩ-cm, and we targeted these values for the experiment.

For conductor 2 of the hybrid coupler, we want a material that will strongly increase the reflectivity when the gap goes to zero. Thus, we want conductor 2 to be a good metal. For our calculations and experiment we chose aluminum.

We first calculated reflectance as a function of wavelength and angle for a large gap, where the hybrid coupler acts as a pure Kretschmann coupler without interference from conductor 2. A contour plot of the calculated reflectance spectra vs angle and wavelength reveals two regions beyond TIR that have strong attenuation. One is near 2.1 μm wavelength and ~58°. The second is 4.5 μm wavelength and ~52°. We then calculated reflectance as a function of the gap at each of these two minima. The results are presented in Fig. 6. The mid-wave IR curve features a broad range of gap from 1 to 7 μm over which the reflectance decreases exponentially by 2 decades per μm. The short-wave IR curve features a narrow range of exponential decrease by about 6 decades per μm. The maximum change in reflectance is ~7 orders of magnitude. One feature is that at large gap, the reflectance changes very slowly with the gap, which allows very fine control at low reflected intensities. On the other hand, the ability of the hybrid coupler to handle high laser powers depends on the heat-sinking capability of the prism. The thermal conductivities of sapphire and CaF₂ are significantly less than that of Al. An infrared transparent semiconductor such as silicon would provide much higher thermal conductivity, but the high index of most semiconductors combined with free-carrier absorption causes them to make poor IR-SPP prism couplers [24].

Fig. 7 presents experimental reflectance as a function of angle for two different gaps. The GZO resistivity was measured to have the same 0.6 mΩ-cm value as used in the simulation. However, the measured GZO thickness of 195 nm exceeded the 152 nm value found to optimize the calculated attenuation. The different values of d were obtained by varying the pressure between the conductor 2 plate and the prism. The blue curve labeled “large d” shows the expected SPP resonance. The green curve labeled “small d” corresponds to a gap that is sufficiently small to quench the SPP creation on conductor 1, which increases the reflectance twofold. Though the experimental apparatus and GZO thickness were unoptimized, this first experiment suffices to demonstrate the principle of variable IR reflectance using the hybrid coupler.

5. Discussion and summary

A number of other IR laser attenuators are known besides those already mentioned in the introduction. A gas cell with actively-controlled pressure has been proposed as a means of protecting IR detectors from intense laser radiation [25]. A gas cell with variable beam path has also been proposed [26]. Modulation of attenuation would be slow using mechanically controlled valves or mirrors.

A combination of spatial filtering and spatially-varied dielectric coatings has demonstrated attenuation by up to 100,000 times for a CO₂ laser by mechanical translation of the attenuator [27]. Similarly, a combined venetian-style attenuator with pinhole spatial filter has been described [28]. These methods would also be slow.

A double prism approach to CO₂ laser attenuation, which is based on gap-variable frustrated total internal reflection, has been described [29,30]. Over 100 dB of attenuation has been demonstrated [31]. Movement of a bulky second prism would be slow in comparison to movement of a thin, potentially MEMS-actuated, conducting film, as described here.

A laser attenuator based on variable scattering in an ion-doped liquid crystal was demonstrated recently out to 3 μm wavelength [32]. The maximum range of attenuation was unspecified, but the attenuation could be on-off modulated at 240 Hz. The maximum attenuation was stated to depend on modulation frequency.

Optically-excited free carriers in a semiconductor have been used to attenuate or modulate the output of THz lasers [33,34]. This method is unlikely to be effective at the shorter mid-infrared wavelengths where free carrier absorption is much weaker.

Over 5 orders of laser attenuation in the near IR below 1.5 μm wavelength has been achieved using photochromic materials with response time of several seconds [35]. Numerous other means of near-IR attenuation are known, but the focus of our work is on longer wavelengths, so we will mention only this one example.

In summary, we have described two designs for an IR laser attenuator with potentially high dynamic range and modulation speed. Both
designs were based on resonant excitation of surface plasmon polaritons on conducting surfaces using prism couplers. The Otto coupler comprises a prism and single conductor surface separated by a variable gap, where the innovation is in the realization that the conductor should be chosen to have an infrared plasma frequency. This configuration in principle could handle high laser powers, but control of attenuation beyond 10000x would require impractically fine positional control. The second design, a hybrid coupler, comprises a thin conducting film on the prism itself, again with IR plasma frequency, separated by a variable gap beyond 10000x would require impractically fine positional control. The principle could handle high laser powers, but control of attenuation by a factor of up to 10 million. Preliminary experiments demonstrated the principle of each design.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments and disclosure

This work was supported by an U.S. Air Force STTR Phase II contract FA865118C0073 and the Florida High Tech Corridor Council. PNF and REP are part owners of Truventic LLC and may benefit financially from the outcome of this research.

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