Fabrication and optimization of uniform output couplers for far-infrared lasers

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An improved technique for the fabrication of uniform output couplers for far-infrared lasers has been developed. The technique includes a process for uniformly removing material from the back side of the coupler's substrate to tune the coupler's reflectivity precisely to the specified value for a particular laser line. Depending on the condition of the coupler after use, it can be retuned to another laser line, which lies within the coupler's reflectance envelope. Furthermore, when there is the possibility of lasing at two different laser wavelengths (as happens with some far-infrared lasers), it is possible to optimize the coupler for one wavelength while at the same time detuning the other wavelength. The fabrication and optimization of these devices are discussed.

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The output coupler is one of the critical components of a CO_2-pumped, far-infrared (FIR) molecular gas laser. The coupler controls the amount of FIR radiation that is reflected back into the laser cavity while allowing a certain percentage of FIR radiation to be transmitted. The most common types of FIR coupler are the hole coupler and the uniform coupler. As the name implies, the hole coupler consists of a metallized-front-surface mirror with a hole that allows a percentage of the FIR radiation in the laser cavity to escape. Hole couplers have the advantage of being relatively inexpensive to manufacture and can be used for a wide range of laser lines. Disadvantages include larger sidelobes in the laser profile owing to hole diffraction and inability to control the polarization of the transmitted radiation. A uniform output couplers,[1–3] on the other hand, uses its entire surface to control the percentage of transmitted radiation, and, depending on the coupler pattern used, the polarization can be controlled. A typical uniform output coupler consists of a transparent substrate coated with a dielectric stack (DS) for high reflectivity at the CO_2 pump-laser wavelength, to which a metallic strip or a mesh pattern is applied. The use of uniform couplers has gained popularity because it permits higher laser output power and improved Gaussian beam profiles.[4]

This Letter discusses the fabrication and optimization of uniform output couplers for FIR lasers that use gold-strip patterns and high-resistivity silicon wafers. It is demonstrated that the reflectance of a FIR uniform output coupler can be precisely tuned by uniform removal of material from the back side of the coupler's substrate.

Typical uniform output couplers have reflectivities that vary rapidly with frequency as a result of multiple internal reflections within the FIR transparent substrate. For example, Fig. 1 shows the FIR reflectance spectrum of a uniform output coupler consisting of gold strips on a DS-coated silicon substrate. The reflectance (R) data were calculated from the measured transmittance (T_{expt}) by assumption of negligible absorption loss ($R \approx 1 - T_{expt}$). It is difficult to design a uniform output coupler to have a specific reflectivity because the application of the DS and the metallic pattern can slightly shift the reflectance spectrum in frequency. Because the reflectance changes rapidly with frequency, a small, unpredictable shift of the spectrum in frequency can change the reflectivity to any value within the reflectance envelope. For the data in Fig. 1, this envelope is more than 30% wide near 1.5 THz. A traditional solution to this problem is to fabricate several couplers with a variety of substrate

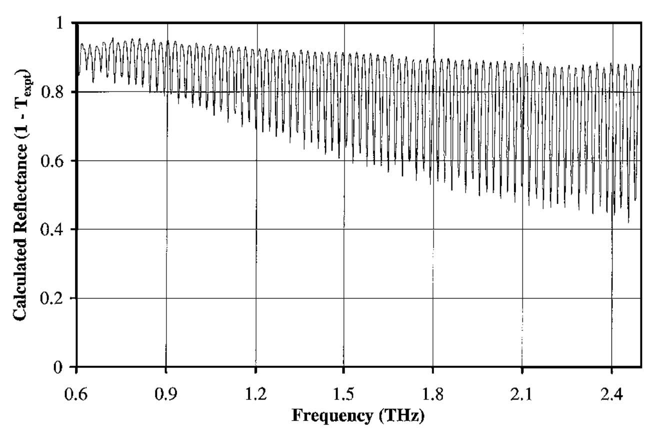

Fig. 1. Calculated FIR reflectance ($R \approx 1 - T_{expt}$) of a prethinned coupler with the strips aligned parallel to vertically polarized radiation.

thicknesses (i.e., with a range of substrate reflectivities), with the hope that at least one of the finished couplers will have the desired reflectivity (typically in the range 85–95%). This procedure requires expensive polishing of several substrates as well as processing of their DS's and metallic patterns.

As a more efficient solution, we have developed a procedure to tune the reflectivity of a postfabricated coupler. Therefore only a single coupler need be fabricated to satisfy the requirements at several laser wavelengths. Our process uses a chemical etching technique, which can be used to shift the reflectance spectrum so that the desired reflectivity occurs at the operating laser line. Since the fringes in Fig. 1 are so close together, only a small shift of the spectrum is necessary to change the reflectivity significantly. If the operating laser line changes, the coupler can be retuned to the proper reflectivity for this new laser line by use of our process.

The coupler discussed in this Letter was fabricated with an ≈38-mm-diameter, high-resistivity silicon wafer that was polished into a plane-parallel etalon approximately 1.8 mm thick. The coupler was designed for use in a FIR laser operating at the 1.563-THz difluoromethane line. Before application of the gold-strip pattern, a DS designed for high reflectivity at the CO_2 pump laser wavelength ($\lambda \approx 9.6\ \mu m$) was deposited onto the polished wafer (Fig. 2). The gold-strip pattern was subsequently applied to this substrate by use of a photolithography process similar to those found in the literature.[5,6] Our strip-fabrication procedure began with thorough cleaning of the substrate with solvents, followed by a 105 °C dehydration bake for 15 min to remove any water. To ensure proper photoresist adhesion we primed the substrate for 2 min in hexamethyldisilizane vapor. A thin film (~1 μm) of Clariant AZ 5214-E IR negative photoresist was spun onto the substrate at 4000 rpm and baked for 30 min at 90 °C. We imprinted a strip pattern in the photoresist by covering the substrate with a chromium-strip photomask and exposing it for 15 s under a standard mercury arc lamp (≈500 W). To promote sharp development of the strip features, we baked the substrate for 7 min at 105 °C in a convection oven, followed by flood exposure under the mercury arc lamp for 2 min. To complete the photolithography we developed the substrate in Shipley MF-319 developer for 1 min. Once the substrate was thoroughly rinsed and dried, it was placed in an electron-beam evaporator, and approximately 100 nm of gold was deposited onto its surface. By use of an ultrasonic acetone bath, the excess gold was lifted off and the photoresist was dissolved, leaving only the gold-strip pattern.

The reflectance behavior of the finished coupler was determined with a Bruker IFS 66v interferometer equipped with a 23-μm-thick Mylar beam splitter, a liquid-helium-cooled silicon bolometer detector, and a Hg arc lamp that was vertically polarized with a wire-grid polarizer. The coupler's strips were aligned parallel to the vertically polarized radiation. To simplify the measurement procedure we acquired transmittance data and calculated the reflectance spectrum, using $R \approx 1 - T_{\mathrm{expt}}$. The experimental uncertainty of the transmittance data is ±1%. We have observed that during the fabrication procedure the reflectance spectrum shifts unpredictably in frequency, making it difficult to design a coupler that has a specific FIR reflectivity at a certain frequency.

Using the above-mentioned technique, one can adjust the coupler's reflectance to the desired value at a certain frequency by backthinning the coupler's silicon substrate with a chemical wet etch consisting of nitric, acetic, and hydrofluoric acids. Before the coupler was thinned with the acid mixture, a layer of Clariant AZ P4620 photoresist was applied to the gold-strip side of the coupler as a protective layer. This photoresist was applied at 1500 rpm for 60 s and baked for 45 min at 105 °C; this slow spin speed was required so that a sufficiently thick layer would be formed. The coupler was secured to the thinning apparatus (Fig. 3) and etched for a short period of time by use of a rotation rate of 45 rpm. The data show that our acid mixture removes silicon at a rate of approximately 2 μm/min. After thinning, the mounted coupler and fixture were immediately rinsed in deionized water for 2 min to remove any residual acid. We removed the coupler from

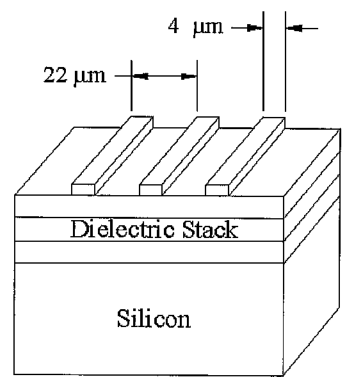

Fig. 2. Schematic of the coupler (not to scale). The pattern consists of 4-μm-wide gold strips spaced every 22 μm. The strip pattern covers the entire surface of the coupler and is approximately 100 nm thick. The multilayerd dielectric stack is designed for high reflectivity at the CO_2 pump-laser wavelength.

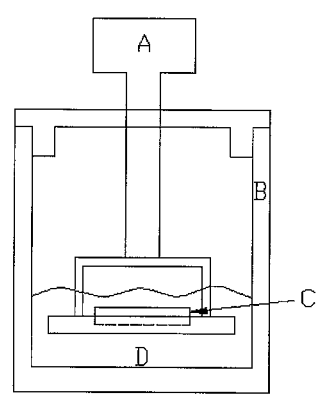

Fig. 3. Apparatus used to thin the coupler's silicon substrate. A, motor running at a constant speed of 45 rpm; B, high-density polyethylene vessel; C, coupler's silicon side exposed (facing up) and strip pattern covered (facing down); D, acid etch mixture.

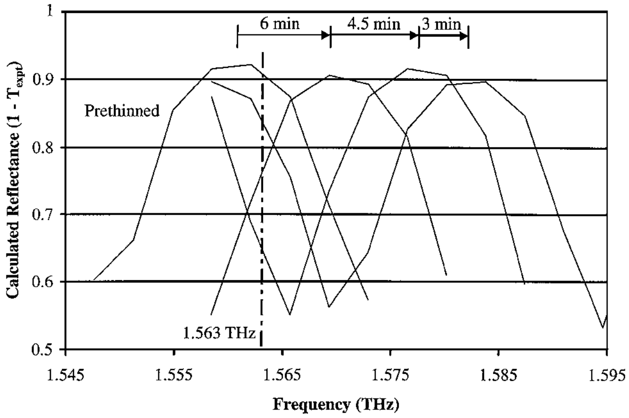

Fig. 4. Calculated FIR reflectance spectra ($R \approx 1 - T_{\text{expt}}$) of the prethinned coupler and after three thinnings. The dashed–dotted line marks the laser frequency of 1.563 THz. For clarity the frequency range has been reduced.

Table 1. Output Coupler Reflectance at 1.563 THz and Approximate Reduction in Silicon Thickness

Thinning	Reflectance at 1.563 THz (%)	Silicon Removed (μm)
Before thinning	91	–
First (6 min)	76	≈12
Second (4.5 min)	65	≈9
Third (3 min)	84	≈6

the thinning apparatus and rinsed it with acetone to remove the protective photoresist layer. Finally, the coupler was remeasured in the interferometer, and the new reflectance spectrum was acquired.

The results from a single coupler, which was repeatedly thinned and characterized, are shown in Fig. 4. The coupler's initial reflectance spectrum and the spectra after three thinning sessions are shown. These four reflectance spectra was acquired at a resolution of ≈3.3 GHz, the limit of our interferometer. Three of the spectra are marked by their thinning durations (6, 4.5, and 3 min), and a dashed–dotted line marks the 1.563-THz laser line. Table 1 lists the reflectances at 1.563 THz for these spectra and the approximate reduction in thickness of the coupler. The range of the reflectance data in Table 1 (65–91%) is approximately equal to the reflectance range near 1.5 THz (64–92%) of the original spectrum (Fig. 1). This result supports our hypothesis that the coupler's reflectance can be tuned to any value within the envelope of its reflectance spectrum.

This thinning technique produces several benefits. If the reflectivity of the coupler at a certain FIR laser line is not optimal, we can thin the coupler to change the reflectivity accordingly. The thinning process can also be repeated many times because only a few micrometers of silicon are removed from the back of the coupler during each session. Assuming that the combined thickness of the DS (~1 μm) and the gold-strip pattern (0.08–0.1 μm) is negligible compared with the thickness of the silicon (≈1.8 mm), a 3-min thinning reduces the overall thickness of the coupler less than 0.2%. Therefore the coupler can be retuned to another reflectivity as often as needed without reducing the coupler thickness greatly. In addition, our repeated thinnings did not damage the coupler's strip pattern.

In summary, uniform FIR strip output couplers have been fabricated by use of a gold-strip pattern applied to a coated, high-resistivity silicon etalon. The reflectivities of these couplers were successfully tuned and retuned with a chemical wet-etch technique. It should also be possible to optimize a coupler's FIR reflectance at a particular laser line while at the same time detuning another laser line. This is beneficial for some FIR lasers, which frequently encounter two competing laser lines. The ability to retune a coupler's reflectivity eliminates the need for keeping a large stock of specifically tuned couplers on hand for all operating FIR lines.

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