Damage threshold and surface distortion measurement for high-reflectance, low-loss mirrors to 100+ MW/cm^2 cw laser intensity

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Abstract: By frequency-stabilizing the output from an Erbium fiber amplifier at 1580 nm to a high-finesse cavity (finesse ~6300) formed by two high-reflectance, low-loss, concave mirrors, we achieve 22.4±2.0 kW intracavity circulating power and 101±9 MW/cm^2 cw intracavity intensities on the surfaces of the mirrors. Repeated experiments show no damage to the mirrors' coating. In addition, small variations of the mirrors' radius of curvature are observed and measured by recording the cavity's transverse-mode range. The mirrors' 10 cm radius of curvature changes as function of laser intensity at a rate of 105 μm/(MW/cm^2).

OCIS codes: (230.4040) Mirrors; (310.1620) Coatings; (350.1820) Damage; (140:4780) Optical resonators.

References

1. N. Uehara and K. Ueda, "Accurate measurement of the radius of curvature of a concave mirror and the power dependence in a high-finesse Fabry-Perot interferometer," Appl. Opt. **34,** 5611-5619 (1995).
2. J. A. Barnes, T. E. Gough, and M. Stoer, "Laser power build-up cavity for high-resolution laser spectroscopy," Rev. Sci. Instru. **70,** 3515-3518 (1999).
3. A. E. Siegman, *Lasers* (University Science Books, Mill Valley, Calif., 1986), p. 762 and 683.
4. J. P. Goldsborough, "Beat frequencies between modes of a concave-mirror optical resonator," Appl. Opt. **3,** 267-275 (1964).
5. L. Ricci, M. Weidemueller, T. Essinger, A. Hemmerich, C. Zimmermann, V. Vuletic, W. Koenig, and T. W. Haensch, "A compact grating-stabilized diode laser system for atomic physics," Opt. Commun. **117,** 541 (1995).
6. R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward, "Laser phase and frequency stabilization using an optical resonator," Appl. Phys. B **31,** 97-105 (1983).
7. E. Hecht, *Optics*, 4th Edition (Addison-Wesley, 2002), p. 594.

1. Introduction

Low-loss and high-reflectance (HR) mirrors are widely used in many applications such as cavity-enhanced wavelength conversion, cavity ring-down spectroscopy, quantum optics, and laser stabilization. When these mirrors are illuminated with high laser intensities, thermally induced distortion and damage are a major concern. Therefore, the measurement of mirror distortion and damage is a key factor for characterizing low-loss and HR mirrors.

As these low-loss and HR coatings are heated, expansion of the optical coating occurs altering the mirror's radius of curvature. Uehara et al. [1] developed an accurate method to measure the radius of curvature for mirrors used in a high-finesse Fabry-Perot cavity. In this technique, laser's frequency was stabilized to a resonance of the cavity. The radius of curvature can be accurately calculated by measuring the cavity's free spectral range (FSR) and transverse-mode range (TMR). In reference [1], a continuous-wave (cw) intensity level of 2.1 MW/cm^2 on mirrors was measured, with a corresponding radius of curvature change of 47-60 μm/(MW/cm^2). Another related work by J. A. Barnes et al. [2] achieved mirror intensities of approximately 3 MW/cm^2. No damage to the mirror's coating was observed in either of these works. To authors' knowledge, these are the highest cw power density on mirrors that have been reported.

In this paper, we report a cw laser intensity of 101 MW/cm^2 on low-loss and HR mirrors with no damage to the mirrors' coating. Using the same method as used in Reference [1], the mirrors' 10 cm radius of curvature is measured to have a 105 μm/(MW/cm^2) intensity dependence.

2. Principle

To achieve the highest possible mirror intensities, we use a standing-wave cavity formed by two concave mirrors. Although a bow-tie ring cavity eliminates the use of optical isolators, it has twice the mirror transmission and absorption losses compared to the standing-wave cavity. As a result, in the ring cavity, the intracavity power is about 4 times smaller than in the standing-wave cavity.

In a standing-wave cavity formed by two concave mirrors, if the radii of curvature of the two mirrors are r_1 and r_2 respectively and the mirror spacing is L, then the cavity's resonant frequencies are [3]

$$\nu = \left\{ q + (n+m+1)\frac{1}{\pi}\cos^{-1}\left[(1-L/r_1)(1-L/r_2)\right]^{1/2} \right\} \frac{c}{2L}, \tag{1}$$

where c is the speed of light in the cavity; q is the longitudinal mode number (equal to the number of half-wavelength in the distance L); m and n are the transverse mode numbers at two orthogonal directions (equal to 0, 1, 2…). Therefore, as depicted in Fig. 1, each transverse mode set (same value of q) are separated by a free spectral range (FSR), while within a transverse mode set, each transverse modes are equally spaced by transverse mode range (TMR):

$$\mathrm{FSR} = \frac{c}{2L}; \tag{2a}$$

$$\mathrm{TMR} = \frac{1}{\pi}\cos^{-1}\left[(1-L/r_1)(1-L/r_2)\right]^{1/2} \frac{c}{2L}. \tag{2b}$$

We use two identical concave mirrors in our experiment (r_1=r_2). The TMR therefore simplifies to:

$$\mathrm{TMR} = \frac{1}{\pi}\cos^{-1}(1-L/r)\frac{c}{2L}. \tag{3}$$

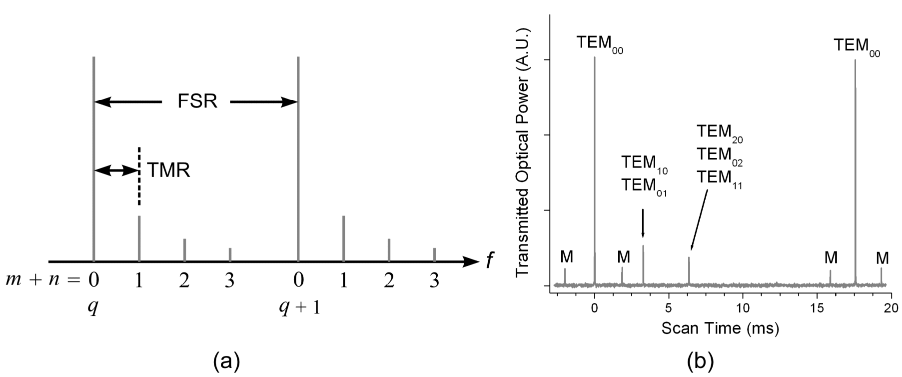

Fig. 1. (a) Resonant frequencies in a standing-wave concave-mirror cavity. Each longitudinal mode contains a set of transverse modes. The separation between two adjacent longitudinal modes is the free spectral range (FSR), while the two adjacent transverse modes are separated by the transverse mode range (TMR). (b) Experimental cavity transmitted signal as the cavity is scanned (for showing purpose, the mode-matching is not optimized). The two identical mirrors have a radius of curvature r = 10 cm and are separated by L = 1.45 cm. Thus FSR = 10.35 GHz and TMR = 1.80 GHz. Peaks labeled "M" are the modulated sidebands on the laser for measuring purpose (see text).

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If the FSR and TMR can be measured, the exact values of cavity length L and mirror's radius of curvature r can then be calculated. Measurement of cavity mode spacing was first performed by J. P. Goldsborough [4] in 1964. He measured beat frequencies between the resonant modes of a He-Ne laser resonator with concave mirrors. This technique was later used by N. Uehara et al. [1] to measure the FSR and TMR and consequently the mirror's radius of curvature. In this technique, the laser's frequency is locked to the cavity's TEM_{00} fundamental mode. To measure the TMR the laser is frequency modulated. The modulation adds frequency side-bands on the laser's carrier frequency (see Fig. 1(b)). Note that although Fig. 1(b) is the transmitted signal when the cavity's length is scanned, it is equivalent to scanning the laser's frequency at a fixed cavity length. Thus when the modulation frequency is equal to any of the TEM_{mn} resonant frequencies, the upper sideband becomes resonant together with the TEM_{00} mode at the same cavity length. Both modes will pass through the cavity and the beat frequency between them can be detected by a detector. So a high-speed optical detector is used to receive the cavity transmitted signal and an RF spectrum analyzer is used to measure the beat frequency.

In Ref [1], two mirrors, one flat and one concave (r = 1 m), were used to form the standing-wave cavity. The laser was a 200 mW Nd:YAG laser at 1064 nm. The results are summarized as follows:

1. An intracavity circulating power of 5.6 kW was reached and the intensity at the beam center was 2.1 MW/cm^2. The cavity transmitted power was linearly increased with the incident power; no saturation effects were observed. This showed that damage threshold was not yet reached at the 2.1 MW/cm^2 intensity level.
2. It was measured that the cavity's FSR did not change as a function of incident laser power. This was because the cavity was locked to the laser's frequency (fixed), thus the cavity length must remain constant.
3. It was measured that the cavity's TMR decreased with the increasing laser intensity. This indicated that the concave mirror's radius of curvature increased as a function of laser intensity and was measured to change at a rate of 43-60 μm/(MW/cm^2).

In this paper, we report an intensity level of 101 MW/cm^2 on the surface of the mirror. To our knowledge, this is the highest cw intensity achieved on mirrors. Damage threshold is still not reached at this high intensity level. The mirror's 10 cm radius of curvature is measured to change with laser intensity at a rate of 105 μm/(MW/cm^2).

3. Experiment

Figure 2 shows the experimental setup. An Erbium fiber amplifier (IPG Photonics EAR-50K-C-SF) at 1580 nm is used as the laser source. The amplifier is seeded by an external-cavity diode laser (ECDL) with a Littrow feed-back grating [5]. The Littrow external-cavity configuration [5] narrows the diode laser's linewidth to ~1 MHz level on 1 ms time scales. An anamorphic prism pair is used to circularize the elliptical spatial profile of the ECDL beam. Two Faraday isolators with ~ 70 dB combined isolation minimize the optical feedback to the ECDL. A free-space electrooptic modulator (EOM; New Focus 4003) adds 15 MHz phase modulated side-bands to the laser carrier frequency. This is required for Pound-Drever-Hall laser/cavity stabilization [6]. The beam is then coupled into a fiber EOM (EOspace, 0-20 GHz) for measuring the cavity's TMR. Finally, about 2 mW seed laser is amplified by the Erbium fiber amplifier to a maximum 50 W power level.

The output light from the Erbium fiber amplifier is unpolarized. After passing through two polarization-independent, high power optical isolators, the laser beam is mode-matched into the high-finesse cavity (HFC) formed by our low-loss and HR mirrors. The two mirrors are identical and have a radius of curvature of 10 cm. The distance between the two mirrors is about 1.45 cm. This cavity is thus between the nearly-planar and the confocal configurations and is stable [7]. A 2.5-inch-long PZT tube is attached to the back mirror for adjusting the cavity length. A wedged glass is placed in front of the cavity for obtaining a small amount of the incident and the cavity-reflected light (measured by D1 and D2 respectively). Behind the

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cavity, a slow detector (D4) is placed to measure the transmitted power and a fast detector (D3) to measure the cavity modes beat frequencies.

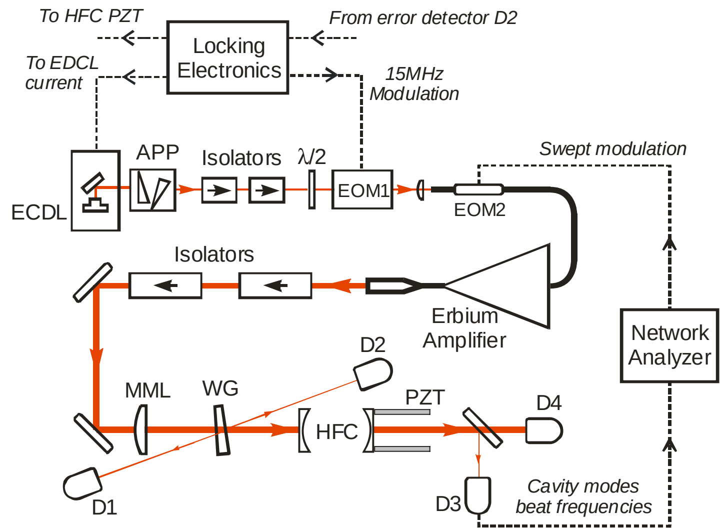

Fig. 2. Experimental setup. The laser source is an ECDL-seeded Erbium Amplifier. The Pound-Drever-Hall technique is used to lock the laser's frequency to the cavity. ECDL: external-cavity diode laser, APP: anamorphic prism pair, λ/2: half-wave plate, EOM1: electrooptic modulator (free space), EOM2: electrooptic modulator (fiber coupled), MML: mode-matching lens, WG: wedged glass, HFC: high-finesse cavity, PZT: piezo-electric transducer, D1: detector for monitoring input laser power, D2: detector for cavity reflected signal, D3: high-speed detector for measuring beat frequency between cavity modes, D4: detector for monitoring transmitted power.

The mirrors have low-loss and HR coatings (by Advanced Thin Films) on the curved sides of concave, fused silica substrates. An anti-reflection coating is applied on the planar sides. For these mirrors, a transmittance (T) of 460 parts per million (ppm) at 1580 nm is measured by the manufacturer, whereas our measurement gives T = 495 ± 30 ppm. The reflectance of the mirrors is thus $R \approx 0.9995$, ignoring the absorption. This gives a finesse of 6280 of the cavity.

Geometrical and other parameters of the cavity are listed in Table 1.

Table 1. Key parameters of the cavity

r	L	FSR	TMR	z_0	w_0	w_m
10 cm	1.45 cm	10.35 GHz	1.80 GHz	2.59 cm	114 μm	119 μm

Notations: r = radius of curvature of the mirrors, L = cavity length, FSR = free spectral range, TMR = transverse mode range, z_0 = Rayleigh range of the cavity's TEM_{00} transverse resonant mode, w_0 = beam radius at the waist of the TEM_{00} mode, w_m = beam radius on surfaces of the mirrors.

Laser beam is mode-matched into the TEM_{00} resonant mode of the cavity. The Pound-Drever-Hall technique [6] is used to lock the laser's frequency to the cavity's resonance. A 15 MHz RF modulation (EOM1) is applied to laser. By detecting and demodulating the reflected beam, an error signal is generated. Our electronic servo sends a feedback to ECDL's current controller for fast correcting the laser's frequency. At the same time another feedback is sent to the cavity's PZT controller for slowly correcting the length of the cavity.

When the laser's frequency is locked to cavity's resonance, another RF modulation swept around the cavity's TMR (1.8 GHz) is applied to EOM2. This generates a frequency component near the cavity's $TEM_{01(10)}$ resonant mode. A high-speed detector (New Focus

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1611) measures the transmitted light and detects the beat signal between the TEM_{00} and $TEM_{01(10)}$ modes. A network analyzer (HP8594E) records the spectral trace of this beat signal.

The method of calculating the intracavity intensity on the surfaces of the mirrors is as follows. When the laser's TEM_{00} mode is locked with the cavity, the transmitted laser power P_t is measured. The intracavity circulating power P_c, for small mirror absorptions, is then given by

$$P_c = P_t / T \, . \tag{4}$$

On the surfaces of the mirrors, the intensity at the beam center is calculated by

$$I = \frac{2P_c}{\pi w_m^2} , \tag{5}$$

where $w_m = 119\ \mu$m is the $1/e^2$ beam radius on surfaces of the mirrors.

4. Data

Figure 3 shows the power measurements. Figure 3(a) is the measured transmitted power as a function of the input power. The cavity coupling efficiency is found to be at least 72%. (Higher-order spatial modes of the laser beam, modulated sidebands, and mirror absorptions are the main causes for not reaching the 100% coupling). We note that at higher power there is slight saturation effect, indicating the fact that distortion of the mirrors' coating degrades the laser-cavity mode matching.

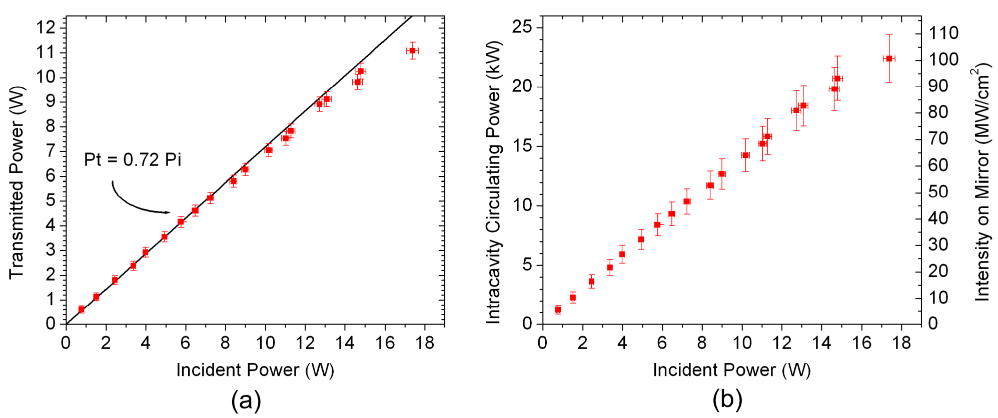

Fig. 3. Power and intensity data. (a) Transmitted power as a function of the incident power. The linear fitting shows a 72% slope. (b) Converting the transmitted power to the intracavity circulating power and the beam-center intensity on the surfaces of the mirrors. Peak values of 22.4 ± 2.0 kW circulating power, or 101 ± 9 MW/cm^2 intensity on mirrors are achieved at the 17.4 W incident power.

Figure 3(b) plots the calculated intracavity circulating power and the intensity on mirrors (at beam-center) using Eqs. (4) and (5). Peak values of 22.4 ± 2.0 kW circulating power, or 101 ± 9 MW/cm^2 intensity on mirrors are achieved at the 17.4 W incident power. To our knowledge, this is the highest reported cw laser intensity on mirrors.

An important fact is that we are able to repeat the same measurement and obtain the similar slope as measured in Fig. 3(a). This indicates that the mirrors' coating is not permanently damaged even at the high 100 MW/cm^2 intensity level. However, after each measurement, we must re-mode-match the laser and cavity, i.e., slightly re-adjust the relative orientation of the laser beam and the cavity in order to reach the same-level cavity coupling efficiency. This indicates that the mirrors' coating experience temporary distortion by high intensity and thus the mode-matching is reduced. Redirect the laser beam to different spots on

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mirrors, in other words, making use of "cold" undistorted coating area, is necessary to re-optimize the mode-matching.

The distortion on mirrors' coating is quantitatively demonstrated by measuring the radii of curvature of the mirrors. First, cavity's TMR is measured by detecting the beat frequency between the cavity's TEM_{00} mode (locked) and $TEM_{01(10)}$ mode (swept by RF modulation). The spectra of this beat signal measured by the network analyzer are shown in Fig. 4. The beat frequency, or the TMR, becomes smaller as the laser intensity on mirrors goes higher.

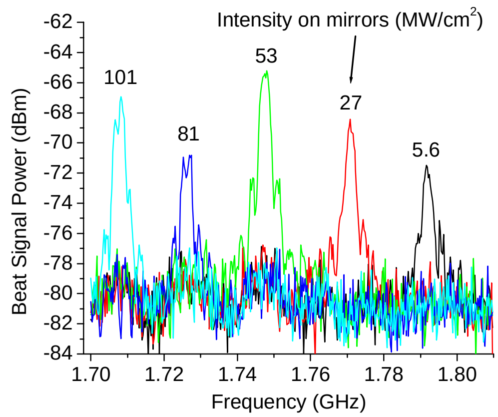

Fig. 4. A few selected traces of the network analyzer showing the spectra of the beat signal between the cavity's fundamental transverse mode (locked) and the first-order transverse mode (swept by RF modulation). The peak (equal to cavity's TMR) moves to smaller frequency direction as the intensity on mirrors increases. The resolution bandwidth of the network analyzer is set at 100 kHz.

The "peak search" function of the network analyzer is used to read the peak frequency (i.e., TMR) and the readings are recorded by computer. Figure 5(a) shows the TMR as a function of the intensity on mirrors. A slope of -0.92 MHz/(MW/cm^2) is measured.

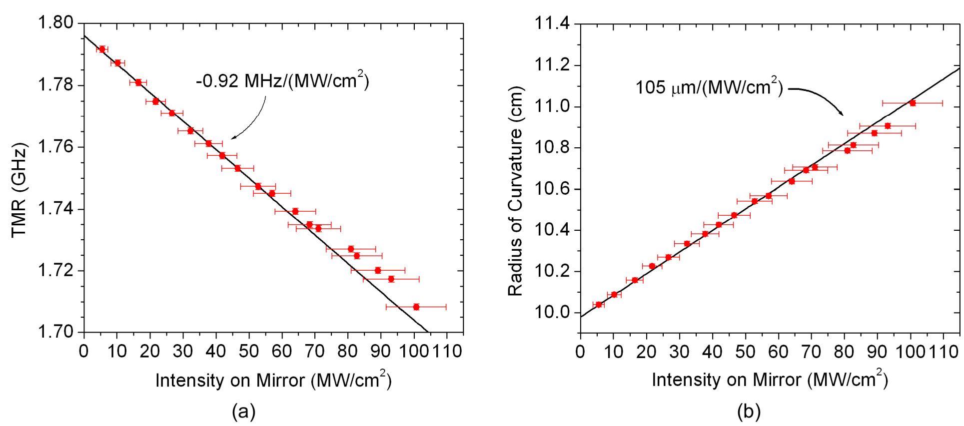

Fig. 5. (a) Measured transverse mode range (TMR) as a function of the intensity on mirrors. (b) Convert TMR into mirrors' radius of curvature. It is found that the radius of curvature increases with the increasing intensity at a rate of 105 μm/(MW/cm^2).

The next step is to calculate the mirrors' radius of curvature using Eq. (3). The free spectral range of the cavity is an essential value for this calculation. However, we do not have a fast detector to measure frequencies around 10 GHz range. Instead, we assume that the mirrors' radius of curvature is exactly 10 cm at zero intensity. Then from the linear fitting in

Fig. 5(a), we found that at zero intensity TMR = 1.796 GHz. Using Eq. (3), we calculate that FSR = 10.35 GHz or L = 1.45 cm. The FSR or L remains constant at high intensities because the cavity is locked to the laser's frequency. This fact was shown in Ref [1] and was also demonstrated by us using a long cavity. Knowing the accurate values of FSR or L, the mirrors' radius of curvature can then be calculated at high intensities using Eq. (3). Figure 5(b) plots the radius of curvature as a function of the intensity on mirrors. Linear fitting of data gives a distortion rate of 105 μm/(MW/cm^2).

5. Discussion and Summary

We realize an extremely high cw laser intensity to a level of 100 MW/cm^2 on the low-loss and HR mirrors. Due to thermal heating by the absorption loss, the dielectric coatings on mirrors are distorted and eventually could be damaged at high intensities. In this paper, we demonstrate that the damage threshold is higher than 100 MW/cm^2. This provides a useful reference to many applications using low-loss and HR mirrors.

Furthermore, we quantitatively measure the distortion of the mirror coating. By detecting the beat signal between the transmitted fundamental mode (locked) and the first-order transverse mode (swept by RF modulation), we measure the transverse mode range and thus the mirrors' radius of curvature. It is found that mirrors' radius of curvature increases with the intensity on mirrors at a rate of 105 μm/(MW/cm^2). In other words, the curved sides of mirrors become more and more flat as the intensity increases. This says that the mirrors' thin-film coating expands because of the thermal heating – it is a reasonable phenomenon.

Since the laser's frequency is fixed and meanwhile the cavity is locked to it, the cavity's length must remain constant at any intracavity intensities. But because the mirrors' radius of curvature is changed with the increased intensity, the cavity's PZT servo has to provide a compensating voltage to keep the cavity length at a constant. We do observe this phenomenon. The voltage applied on the cavity's PZT is changed by tens of volts during the each measurement.

Compared to the work done by Uehara et al. [1], they used one planar mirror and a concave mirror to form the cavity. Since the TMR is a function of $(1 - L/r)$, the effect of the flat mirror ($r = \infty$) on TMR is much smaller than that of the concave mirror. In contrast, in this paper, we use two identical concave mirrors. As for which method provides more accurate measurement on concave mirror's radius of curvature, it is not clear. In this paper, we also place the two concave mirrors as close as possible in order to achieve high intensities on mirrors. The only drawback is that the free spectral range is beyond our detector's detecting capability. But we can deduce the FSR quite accurately from the TMR measured at low power.

In summary, we report the highest cw laser intensity ever realized on low-loss and HR mirrors. This study provides important information to the thin-film coating industry and all applications involving these mirrors.

Acknowledgments and Distribution Statement

This work is supported by the Defense Advanced Research Projects Agency (DARPA) of the Department of Defense (DoD), and is approved for Public Release, Distribution Unlimited.