Precision measurement of ultralow losses of an asymmetric optical microcavity

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The losses of the transmission, absorption, and scattering of optical mirrors govern the extraction efficiency of a nonclassical state that is generated inside a cavity. By measuring the reflectivities and transmittances and the matching factors from both sides of a super-mirror-made microcavity at various mode-matching efficiencies, the transmission losses and the unwanted losses, including the absorption and scatter losses, of the left and right cavity mirrors were both determined at the parts-per-million level. © 2006 Optical Society of America

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The Fabry–Perot cavity with high finesse has played an important role in modern experimental optics research, especially in cavity-enhanced optical spectroscopy,[1] such as cavity ringdown techniques,[2] high-precision optical measurement in gravitational wave measurement,[3] laser frequency stabilizations,[4] and quantum optics and atomic physics.[5,6] To reach the strong interaction between atom (ion) and photon,[6] ultra-low-loss mirrors with losses at the parts-per-million (ppm) level, the so called super mirror, are made and used in cavity quantum electrodynamics experiments.[6] The super cavity, which is built by such super mirrors, usually has finesse as high as 10^6.[7] Together with the atom manipulation, it is now an important system for atom–photon entanglement and quantum state generations. The losses of the transmission and other unwanted losses (absorption and scattering) of the optical mirrors govern the extraction efficiency of a nonclassical state that is generated inside a cavity. Large unwanted losses of the cavity mirrors limit the information extraction for intracavity quantum states, which can be known by measuring cavity output fields.[8] Building a microcavity with ultralow unwanted losses and determining the unwanted loss and effective (transmitted) loss are important issues. The usual method of measuring the mirror losses is the cavity ringdown technique (CRDT),[5,9] but there are actually some problems in the experiment: First, CRDT does not work well for the microcavity even with super mirrors, so people usually use the same mirrors to build a long cavity and get the cavity ringdown signal, then determine the losses of the cavity.[7] But during the process of building the microcavity with the same mirrors, the mirror's losses might have been changed; thus we need a measurement in real time for an already-made microcavity. Second, supposing the losses do not change during the process of building the microcavity, the losses we got are the total losses of the cavity. Usually, researchers assumed that both mirrors are identical and then deduced the losses of each mirror.[10] Third, even if the losses of each mirror are known, the ratio between the transmission loss and other unwanted losses still remains unknown. Although by using some methods, such as mirror absorption-induced optical bistability, the absorption coefficients can be precisely measured,[11] but there are still some other losses, such as scattering losses and diffraction losses, which cannot be determined. In 2001, Hood *et al.*[10] proposed a direct measurement and determined the transmittance and other unwanted losses of super mirrors under the assumption of a symmetric cavity and in the case in which the unwanted losses are much less than those of the transmittance. This method has been successfully used to measure the super-mirror losses at 1064 nm.[12] In this paper we have considered the general situation in which the cavity is asymmetric; i.e., each mirror has its own transmittance and unwanted losses. By sending the probe beams on both sides of the cavity and measuring the reflectivities and transmittances as

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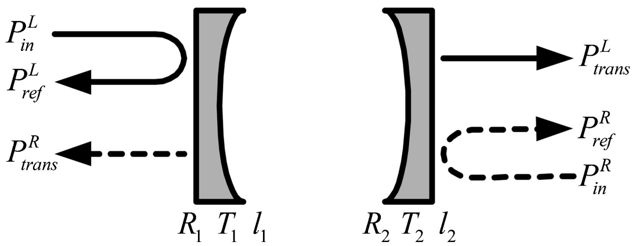

Fig. 1. Schematic of an optical cavity and its transmissions and reflections.

well as the mode-matching factors, the wanted and unwanted losses for each individual cavity mirror are precisely determined at the parts-per-million level.

The basic model is shown in Fig. 1. R_i, T_i, and l_i are, respectively, the reflectivity, transmittance, and extra losses of mirror i, where $R_i + T_i + l_i = 1$ ($i = 1, 2$). First, let us suppose that a light beam is incident to a cavity from left to right and all the light power is perfectly coupled to the TEM_{00} mode of the cavity. When the cavity is resonant with the light field the ratio between the reflected power $P_{\mathrm{ref}}{}^L$ and incident power $P_{\mathrm{in}}{}^L$ is[13]

$$\wp_{(r,L)} = P_{\mathrm{ref}}{}^L / P_{\mathrm{in}}{}^L = \left[\left(\sqrt{R_1} - \sqrt{R_2} + l_1 \sqrt{R_2} \right) / \left(1 - \sqrt{R_1 R_2} \right) \right]^2, \quad (1)$$

and the ratio between the transmitted power $P_{\mathrm{trans}}{}^L$ and incident power $P_{\mathrm{in}}{}^L$ is

$$\wp_{(t,L)} = P_{\mathrm{trans}}{}^L / P_{\mathrm{in}}{}^L = \left[\sqrt{(1 - R_1 - l_1)(1 - R_2 - l_2)} / \left(1 - \sqrt{R_1 R_2} \right) \right]^2. \quad (2)$$

Similarly, if the light is incident from the right side, the ratio between the reflected power $P_{\mathrm{ref}}{}^R$ and incident power $P_{\mathrm{in}}{}^R$ is

$$\wp_{(r,R)} = P_{\mathrm{ref}}{}^R / P_{\mathrm{in}}{}^R = \left[\left(\sqrt{R_2} - \sqrt{R_1} + l_2 \sqrt{R_1} \right) / \left(1 - \sqrt{R_1 R_2} \right) \right]^2. \quad (3)$$

The ratio between the transmitted power $P_{\mathrm{trans}}{}^R$ and the incident power $P_{\mathrm{in}}{}^R$ is the same as in Eq. (2), so we denote both transmitted ratios by $\wp_t$. From Eqs. (1) and (3) the unwanted losses of the two mirrors are extracted as

$$l_1 = 1 - \frac{\sqrt{R_1} - \sqrt{\wp_{(r,L)}} \left(1 - \sqrt{R_1 R_2} \right)}{\sqrt{R_2}}, \quad (4)$$

$$l_2 = 1 - \frac{\sqrt{R_2} - \sqrt{\wp_{(r,R)}} \left(1 - \sqrt{R_1 R_2} \right)}{\sqrt{R_1}}. \quad (5)$$

By substituting these two relations into Eq. (2), the result is

$$(1 - R_2) \sqrt{\wp_{(r,L)} R_1} + (1 - R_1) \sqrt{\wp_{(r,R)} R_2} - \left(1 - \sqrt{R_1 R_2} \right) \times \left[\sqrt{P_L P_R} + (1 - \wp_t) \sqrt{R_1 R_2} \right] = 0. \quad (6)$$

If we consider that the reflectivities are very close to the unit and make the proper approximation, the result is

$$(1 - R_2) \sqrt{\wp_{(r,L)}} + (1 - R_1) \sqrt{\wp_{(r,R)}} - \left(1 - \sqrt{R_1 R_2} \right) \times \left[\sqrt{\wp_{(r,L)} \wp_{(r,R)}} + (1 - \wp_t) \right] = 0. \quad (7)$$

If the cavity finesse is known, we have another relation,

$$F = 2\pi / (2 - R_1 - R_2). \quad (8)$$

From Eqs. (7) and (8) we can get the reflectivities of the two mirrors. Thus the extra losses l_i and the transmittances T_i can also be determined.

In the actual experiment there is always some light that does not couple into the TEM_{00} mode of the cavity so the perfect mode matching cannot be achieved. The light from those higher order modes are reflected when the light field is resonant with the cavity TEM_{00} mode, so the measured ratio $\wp_{(r,i)}{}^m$ ($i = R, L$) of reflected power over the incident power is always higher than that of the perfect mode matching, while the ratio $\wp_{(t,i)}{}^m$ ($i = R, L$) of measured transmitted power over the incident power is lower. Here $i = R, L$ stands for the light incident from the right or left. Let ε_i ($i = R, L$) be the mode-matching factor that is the ratio of the power coupled into the TEM_{00} mode over the total incident power. From $\wp_{(r,i)} = [\wp_{(r,i)}{}^m - (1 - \varepsilon_i)] / \varepsilon_i$ and $\wp_{(t,i)} = \wp_{(t,i)}{}^m / \varepsilon_i$ the measured ratios can be converted to the situations corresponding to the perfect mode matching.[10] Since the spacing of the higher modes of the microcavity is large enough, each higher mode can be identified and thus the mode-matching factor ε_i ($i = R, L$) can be measured by the transmitted spectrum of the microcavity.

Our microcavity was built by using a super mirror with a radius of 10 cm. All the measurements are done at 852 nm. The measured free spectra range is FSR = 3.41 THz, which gives 43.9 μm of cavity length. The transverse mode spacing is TMS = 32.1 GHz. With the help of 300 MHz rf sidebands, the cavity linewidth is determined as $\delta\nu = 47.7$ MHz, so the finesse of the cavity is $F = \mathrm{FSR}/\delta\nu = 7.14 \times 10^4$. To avoid the influence of the birefringence of the cavity mirrors,[10] the incident beam is linearly polarized and the polarization is along one birefringence axis. The reflected beam is coupled out by a polarizing beam splitter with a half-wave plate and a polarization rotator (terbium gallium garnet (TGG) crystal) (see Fig. 2). Two sensitive photodetectors, D1 and D2 (New Focus 2001), are used to detect the reflected and transmitted light from the cavity.

Figure 3(a) shows a set of typical reflected (solid curve) and transmitted (dashed curve) TEM_{00} mode

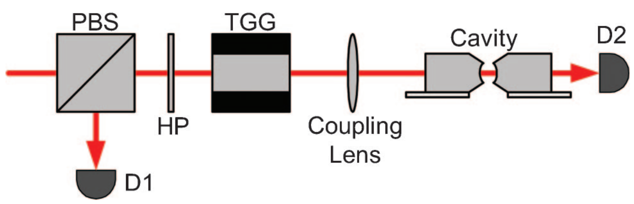

Fig. 2. (Color online) Setup for the left-side incident beam (similar to the right-side incident beam). PBS, polarizing beam splitter; HP, half-wave plate; D1 and D2, two photodetectors.

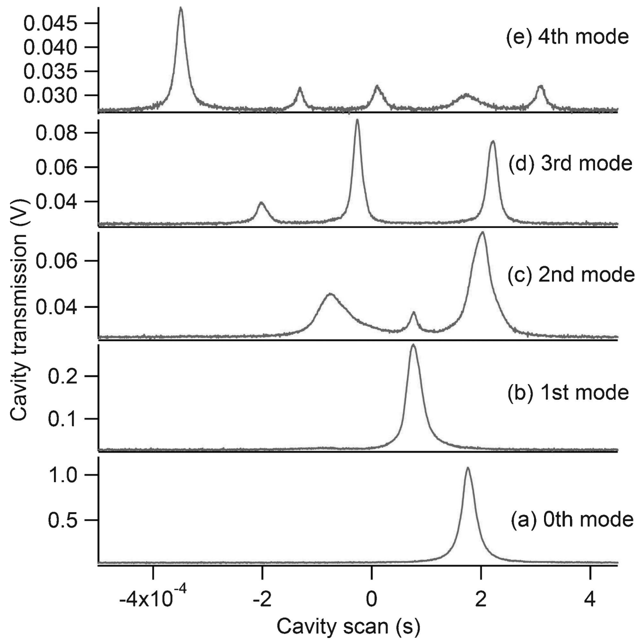

Fig. 4. Higher-order transverse modes. (a)–(e) Zeroth- to fourth-order modes, and the mode-matching factor is determined as 0.652.

spectra of the cavity for a right incident beam when the cavity is slowly scanned over the resonance, where the matching factor is $\varepsilon = 0.652$. The measured ratio of reflected power over the incident power $\wp_{(r,R)}{}^m$ and the ratio of transmitted power over incident power $\wp_{(t,R)}{}^m$ are given by $\wp_{(r,R)}{}^m = V2/V1 = 0.860$ and $\wp_{(t,R)}{}^m = \eta(V3/V1) = 0.00892$, where $\eta = 0.538$ is the total propagation efficiency in the reflected route. Figure 3(b) gives the converted perfect-mode-matching results corresponding to Fig. 3(a); thus we get $\wp_{(r,R)} = 0.786$ and $\wp_{(t,R)} = 0.0137$.

The mode-matching factor is an important parameter in this measurement. To determine this factor precisely, we increase the incident power, and we can clearly observe up to the tenth transverse mode. Figure 4 shows the higher-order modes from the zeroth to the fourth mode. Since the transverse mode spacing is very large, the originally generated transverse modes are separated from each other due to nondegeneracy caused by distortions of the cavity mirrors.[14] Higher-order modes over the tenth mode are very small and can be ignored. The mode-matching factor can then be determined. It is $\varepsilon = 0.652$ in Fig. 4.

We can slightly change the alignment of the incident beam to vary the mode matchings and measure $\wp_{(r,i)}{}^m$ and $\wp_{(t,i)}{}^m$ under various mode-matching factors. Once the mode-matching factors are known, the reflected and transmitted ratios $\wp_{(r,i)}$ and $\wp_{(t,i)}$ corresponding to perfect mode matching can also be obtained. The results are shown in Table 1 (for the right incident beam) and Table 2 (for the left incident beam). We can see that, although $\wp_{(r,i)}{}^m$ and $\wp_{(t,i)}{}^m$ are varied when the mode-matching factor changes, the converted perfect-mode-matching ratios remain almost the same, which clearly shows the reliability of the measurement. We can see that $\overline{\wp_{(r,R)}} = 0.784(3)$ and $\overline{\wp_{(r,L)}} = 0.810(6)$, and the dissimilarity of these two values indicates the asymmetry of the cavity; i.e., the two cavity mirrors are not identical. Similarly, $\overline{\wp_{(t,R)}} = 0.0138(2)$ and $\overline{\wp_{(t,L)}} = 0.0129(6)$, which are very close, and this is in accordance with the above-mentioned theory. Let $\wp_t = (\overline{\wp_{(t,R)}} + \overline{\wp_{(t,L)}})/2 = 0.0134(10)$.[15] From relations (7) and (8) we get the reflectivities of the two cavity mirrors: $R_1 = 0.9999619(3)$ and $R_2 = 0.9999501(3)$, and thus the losses can be determined as $l_1 = 33.2(7)$ ppm and $l_2 = 45.4(6)$ ppm; the transmittances are given by $T_1 = 5.0(9)$ ppm and $T_2 = 4.5(8)$ ppm, accordingly.

In conclusion, we have determined the losses of two different super mirrors that formed an asymmetric micro-optical cavity by measuring the reflectivities and transmittances from both sides of the cavity at various mode matchings. The effective transmission losses and the unwanted losses of the microcavity are both reliably determined at the parts-per-million level. Such a method of measuring the ultralow losses of the cavity can be used easily for all kinds of optical cavities in real time, especially for those already-built super cavities, to monitor the long-term change of the

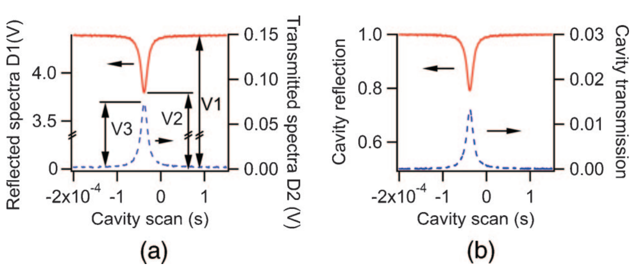

Fig. 3. (Color online) Reflected and transmitted spectra of the cavity TEM_{00} mode for a right-side incident beam (the mode-matching factor $\varepsilon = 0.652$). (a) Original outputs by detectors D1 and D2 and (b) converted perfect-mode-matching TEM_{00} spectra (normalized to 1).

Table 1. Reflectivities and Transmittances for Right Incident Beam

ε	$\wp_{(r,R)}{}^m$	$\wp_{(t,R)}{}^m$	$\wp_{(r,R)}$	$\wp_{(t,R)}$
0.882	0.809	0.01220	0.784	0.0138
0.710	0.848	0.00979	0.785	0.0138
0.652	0.860	0.00892	0.786	0.0137
0.553	0.879	0.00770	0.781	0.0139
0.390	0.916	0.00528	0.786	0.0135
0.180	0.960	0.00248	0.780	0.0138
Mean	—	—	0.784(3)	0.0138(2)

Table 2. Reflectivities and Transmittances for Left Incident Beam

ε	${\wp_{(r,L)}}^m$	${\wp_{(t,L)}}^m$	$\wp_{(r,L)}$	$\wp_{(t,L)}$
0.745	0.857	0.00950	0.809	0.0127
0.722	0.866	0.00901	0.814	0.0123
0.653	0.874	0.00847	0.807	0.0130
0.603	0.887	0.00767	0.813	0.0127
0.538	0.901	0.00680	0.816	0.0126
0.381	0.924	0.00533	0.801	0.0140
Mean	—	—	0.810(6)	0.0129(6)

cavity quality, or for those micro or miniature super cavities where CRDT does not work well.

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