Strong intensity variations of laser feedback interferometer caused by atmospheric turbulence

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The significant variation of the laser output can be caused by feedback of a small part of laser beam, which is reflected or backscattered by a target at a long distance from laser source, into the laser cavity. This paper describes and analyzes theoretically and experimentally the influence of atmospheric turbulence on interference caused by laser feedback. The influence depends upon both the energy of feedback into the laser cavity and the strength of turbulence over a laser propagation path in the atmosphere. In the case of stronger energy of feedback and weak turbulence variance of fluctuation of the laser output can be enhanced by hundreds to thousands times. From our measurements and theoretical analysis it shows that these significant enhancements can result from the change of laser-cavity-modes which can be stimulated simultaneously and from beat oscillations between a variety of frequencies of laser modes. This also can result from optical chaos inside the laser resonator because a non-separable distorted external cavity can become a prerequisite for optical chaos.

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For its many applications of sciences and technologies, there are many interests in research of optical wave propagation through the atmosphere. Most of them, generally, concentrate on research of the atmospheric transmittance because it must be known how much energy of light can be remained at the end of the atmospheric passage. As a consequence, many researchers contribute to study effects of light absorption and scattering in the atmosphere and to develop theoretical models and computer code for practical application. In some cases of utilizing laser signature of coherence and phase, the studies on phase fluctuation of optical wave front caused by atmospheric turbulence are required. Based on our knowledge, for laser application in the atmosphere, it has not been paid enough attention to study special effects when a portion of the light reflected or scattered from a target at a long distance returns back into the laser cavity.

Generally, when the source of laser is not optically isolated from the light reflected or scattered by target, the target having even very weak reflectivity must be considered as a part of the lasing system. The lasing modes and threshold gain of the resulting three-mirror-cavity are therefore modified by atmospheric turbulence between the source-laser and target.

Both knowledges of atmospheric turbulence and quantum electronics are required for this study. We combine the results of these two fields to demonstrate the influence of atmospheric turbulence on output of the laser feedback interferometer theoretically and experimentally.

Since the target plays as a weakly reflecting mirror, we can model the system as a three-mirror Fabry-Perot cavity, and in this way analyze the effect of the target on the mode structure of the laser. Groot *et al.*[1] utilized Fresnel reflectivity used in the modeling of stratified media[2] to obtain lasing condition for the three-mirror system as

$$1 = R^2\left[1 + a\cos(2kL_\mathrm{e})\right]\exp\left[ia\sin(2kL_\mathrm{e})\right]\exp(2in_ckL_\mathrm{d}), \tag{1}$$

where $a = (1 - R^2)r/R$, R is the facet amplitude reflectivity, L_d is the laser cavity length, k is the magnitude of the vacuum wave vector, L_e is the external cavity length (distance between target and source laser), n_c is effective refractive index of the laser active material ($n_c = n + ig$, g is the imaginary part of the effective refractive index), and r is reflectivity of the target.

The threshold gain G_T for the three-mirror system can be obtained by using modulus of Eq. (1)

$$G_\mathrm{T} = -1/(2L_\mathrm{d})\ln\left\{R^2[1 + a\cos(2kL_\mathrm{e})]\right\}. \tag{2}$$

Its phase condition is satisfied by

$$2n_ckL_\mathrm{d} + a\sin(2kL_\mathrm{e}) = 2\pi M, \tag{3}$$

where $M = 0, 1, 2, \cdots$.

In the Eqs. (2) and (3) the influence of air in the external cavity is neglected. Practically, atmospheric turbulence in the external cavity affects significantly the threshold gain and the phase of the lasing system. Mainly fluctuations of both refractive index of air and angle of arrival of laser beam which passed through the atmosphere in the external cavity produce important influence on lasing condition.

If refractive index of air is n_a, then we put its fluctuation Δn_a and fluctuation of angle of arrival of the laser beam $\Delta\theta$ into Eqs. (2) and (3), so that

$$G_\mathrm{T} = -1/(2L_\mathrm{d})\ln[R^2(1 + a\cos(2kn_\mathrm{a}L_\mathrm{e}\cos(\Delta\theta)))], \tag{4}$$

$$2n_ckL_\mathrm{d} + a\sin(2kn_\mathrm{a}L_\mathrm{e}\cos(\Delta\theta)) = 2\pi M, \tag{5}$$

where $n_\mathrm{a} = 1 + \Delta n_\mathrm{a}$.

We can see from Eqs. (4) and (5), the frequency of laser output and the threshold gain of the lasing system can be directly influenced by both fluctuations of air refractive index and angle of arrival of laser beam. The relation of $\mathrm{d}G_\mathrm{T}/\Delta n_\mathrm{a}$ and $\mathrm{d}k/\Delta n_\mathrm{a}$ can be obtained directly by differentiating Eqs. (4) and (5), then the effect of fluctuation of air refractive index on frequency of the laser output and threshold gain of the lasing system can be calculated quantitatively.

Usually, the following formula[3] can be used to describe the influence of atmospheric turbulence in the external cavity:

$$C_n^2 = 1.9\langle\Delta n_a^2\rangle(2\pi/L_0)^{2/3}, \quad (6)$$

where C_n^2 is structure constant of atmospheric turbulence, the bracket $\langle\ \rangle$ denotes the statistical average, and L_0 is outer-scale of atmospheric turbulence.

The influence of atmospheric turbulence on the threshold gain and the frequency of the laser output can be calculated from Eqs. (4), (5) and (6). As an example, under the assumptions for structure constant of turbulence $C_n^2 = 1.0 \times 10^{-16}$ m$^{-2/3}$ and its outer scale $L_0 = 1$ m in the laboratory, if the reflectivity of the target $r = 0.04$, and the length of the external cavity $L_e = 2.34$ m, the change of threshold gain $dG_T = 1.85 \times 10^{-3}$ and the frequency shift $d\lambda = 2.37 \times 10^{-16}$ m of the lasing system can be obtained. It is obvious from these values that both the threshold gain and the frequency shift of the lasing system cannot be neglected even in a case of very weak turbulence.

As for the influence of laser beam angle of arrival produced by turbulence, it can be considered as a laser resonator without exact adjustment of the cavity mirrors in perpendicular to the laser beam. One can find detail discussion in Ref. [4].

The experiments for this study were performed in the laboratory of the University of Florence. The setup of experiment is shown in Fig. 1. Two thin beams from continuous He-Ne laser (Uniphase, Model 1125) with 5-mW power pass through horizontally a layer of turbulence which is 98 cm high from heaters on the ground. One of them (A) is reflected into its laser cavity by a piece of optical glass (G) just in front of the detector. So the space between the optical glass and the output mirror of the laser becomes an external cavity of the laser system. The other beam (B) is without feedback of laser. Therefore, the influence of the external cavity can be measured by comparison of the signals received by two detectors for beam A and beam B, respectively.

The detectors used in the experiments are UDT OP-EYE SC/10D which are lateral effect photodiode. They can be used to measure both the position fluctuations and total intensity on the sensor. The acquisition rate is fixed at 300 samples per second and the duration of each acquisition is set 5 minutes. To compare the influence of energy that feedbacks into the laser cavity, we can change the transmittance of a filter FF which is just in front of the detector for beam A. The filter F is used to be sure in the linear area of detector. The atmospheric turbulence can be changed by using different electrical power of the heaters to prove the effect of atmospheric turbulence on output intensity of the laser system.

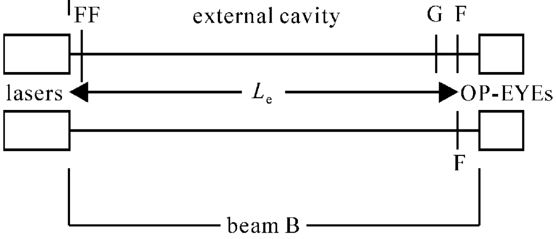

Fig. 1. Experimental setup. F and FF are filters, L_e is external cavity length, G is optical glass, OP-EYEs are photodiodes.

Figure 2 shows a part of measurements' data of intensity variances of laser output under the condition of weak turbulence, where plots (a) and (b) represent with and without strong feedback, respectively. We can find obviously by comparison of Figs. 2(a) and (b) that intensity variance of laser with feedback (a) is much larger than that without feedback (b). Moreover, the beat oscillations between different modes can be seen clearly from Fig. 2(a). Based on our knowledge, the beat oscillation can be observed only when a number of cavity modes can be stimulated simultaneously[5]. This means that several modes with high gain can oscillate simultaneously when there is atmospheric turbulence in the external cavity.

Figure 3 shows that a part of the measurements' data of intensity variances of laser output under room environment and weak feedback condition. Figures 3(a) and (b) represent intensity fluctuations of laser output at different time periods in the 300-second data record. From these plots, it is obvious that beat oscillations are quite different within different time period. The oscillation is not stable, since turbulence itself is a random process.

We can find that frequency of beat oscillation increases with increasing turbulence in the external cavity from comparing Fig. 2(a) with Fig. 3(a).

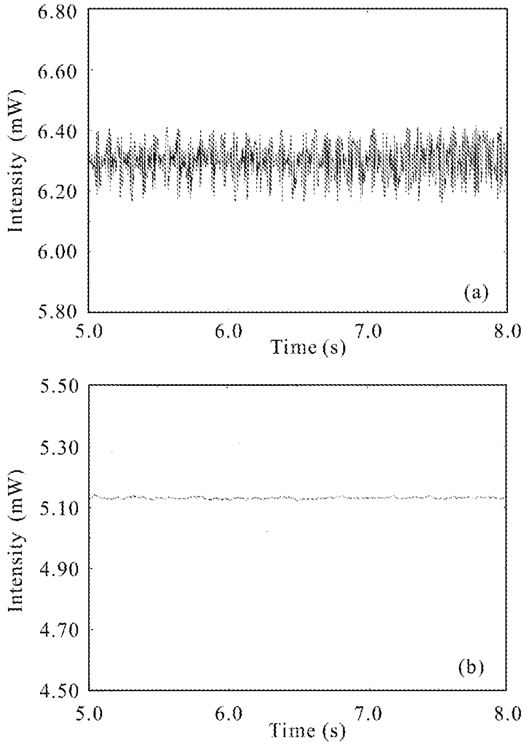

Fig. 2. A part of data measured at Jan. 1, 2002 under the following conditions: weak turbulence (heaters with 400 W power); composite reflectivity = 0.4; length of external cavity = 1.86 m. (a) With and (b) without feedback.

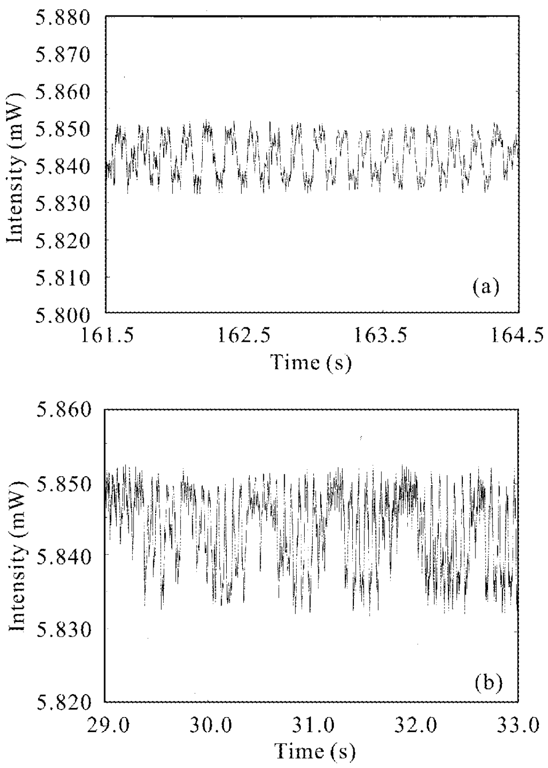

Fig. 3. A part of data measured at Jan. 26, 2002 under the following conditions: room turbulence; composite reflectivity = 0.000225; length of external cavity = 3.74 m. Plots (a) and (b) with feedback for different periods of the data file.

Measured results for ratio of variance of intensity fluctuation at 5 lengths of external cavity are listed in Table 1. From the table we can find that the ratio increases with increasing energy of feedback regardless of different atmospheric turbulence in the external cavity. Especially, in the case of strong feedback, hundreds to thousands times enhancements can be seen for several lengths of external cavity. Based on Eqs. (4) and (5) we can deduce that so large enhancements come from variation of both frequency and mode of laser system. External cavity with atmospheric turbulence acts as the laser cavity without exact adjustment of the cavity mirrors in parallel. There are several modes that oscillating simultaneously. At the mirror the modes interfere each other and produce strong fluctuation of amplitude[4].

From Table 1, we can also find that the ratio is increased obviously with increasing atmospheric turbulence in the external cavity when the heaters change from room temperature to the lowest heat. But the ratio decreases with further increasing atmospheric turbulence. In the case of weak turbulence, the larger part of laser feedback can oscillate in the laser cavity because wandering of laser beam is not very large and fluctuation of angle of arrival is small too. Atmospheric turbulence in the external cavity affects directly output of the laser system. With increasing atmospheric turbulence in the external cavity, energy of feedback into laser cavity is reduced because wandering of laser beam and fluctuation of angle of arrival are increased. As a consequence, influence from the external cavity is reduced clearly in case of strong turbulence. This is very important for application of laser beam in the real atmosphere. As well known, atmospheric turbulence is not so strong if laser over a few meters above the ground or in troposphere, the output power of the laser system will be large variable if very small part of laser that reflected by a target or scattered by aerosol in the atmosphere returns back into the laser cavity.

From Table 1 one can find that the ratio is near 1 at both 1.86- and 3.26-m length of external cavity under the condition of room temperature and low energy feedback. Intensity variance of laser output can not be enhanced at

Table 1. The Measured Variance Ratio of Intensity Fluctuation of Laser Output with Feedback to that without Feedback under the Different Lengths of External Cavity, Different Feedbacks and Different Turbulence of Atmosphere

Length of External Cavity (m)	(Glass + Filter) Composite Reflectivity	Ratio under Electrical Power of Heaters of 0	170 W	400 W	1500 W
1.86	2.25×10^{-4}	1.4	7.4	6.2	8.4
	2.50×10^{-3}	4.6	16.4	11.7	8.8
	4.00×10^{-2}	1671.8	3075.9	1247.1	125.7
2.34	2.25×10^{-4}	22.1	57.9	46.2	34.1
	2.50×10^{-3}	91.1	254.0		55.7
	4.00×10^{-2}	2158.6	4608.0	2014.5	333.5
2.80	2.25×10^{-4}	3.4	14.9	12.7	4.9
	2.50×10^{-3}	23.6	21.0	14.7	5.5
	4.00×10^{-2}	445.8	599.2	209.9	54.6
3.26	2.25×10^{-4}	1.3	7.7	9.1	5.5
	2.50×10^{-3}	1.6	14.0	9.8	6.3
	4.00×10^{-2}	209.4	358.8	91.4	49.6
3.74	2.25×10^{-4}	11.7	21.3	16.5	16.1
	2.50×10^{-3}	45.7	62.5	47.7	26.7
	4.00×10^{-2}	450.0	1296.7	497.2	244.3

these two distances when laser energy feedbacks into the laser cavity. While at the other 3 distances the enhancements appear clearly. These phenomena have been discovered when we adjusted laser spot to the center of the detector before the measurements. This means that the relationship of the enhancement of intensity variance of laser output with the length of external cavity is complicated.

In summary, a very small part of laser reflected into the laser cavity by a target produces laser self interference. We have derived theoretically a formula for calculating the influence of atmospheric turbulence in external cavity on the threshold gain and frequency shift of lasing system. In the case of weak turbulence, we have analyzed why hundreds to thousands times enhancements of variance of intensity fluctuation of laser output can be reached. So large enhancement results from variation of laser modes and from beat oscillation of several cavity modes stimulating simultaneously. It results from optical chaos[6] inside the laser resonator produced by distorted external cavity too. With increasing atmospheric turbulence in the external cavity both wandering and fluctuation of angle of arrival of laser beam are increased. Then the influence of external cavity is reduced because the beam of feedback deviates from the axis of laser resonant cavity. The above conclusion has been proved by the experiment results.

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