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▶ **To cite this version:**

Robbe de Mey, Spencer W Jolly, Alexandre Locquet, Martin Virte. Chaotic time-delay signature suppression in lasers using phase-controlled dual optical feedback. Optics Continuum , 2022, 1 (10), pp.2127-2134. 10.1364/OPTCON.469410 . hal-03870981

HAL Id: hal-03870981

https://cnrs.hal.science/hal-03870981

Submitted on 24 Nov 2022

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Research Article Vol. 1, No. 10 / 15 Oct 2022 / Optics Continuum 2127
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Chaotic time-delay signature suppression in lasers using phase-controlled dual optical feedback

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Abstract: We experimentally study a semiconductor laser subject to two optical feedbacks in a free space setup. We show that control over the feedback phase is essential to adjust the time delay signature in the chaotic output intensity while affecting also the chaotic bandwidth. By optimizing the feedback phase, the time delay signature can be reduced by a factor of more than 2 while maintaining a large chaotic bandwidth.

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Optical feedback in semiconductor lasers can give rise to rich nonlinear behavior in terms of intensity, phase, and carrier dynamics [1–4]. For example, feedback from a distant mirror can destabilize the laser leading to periodic, quasi-periodic, or chaotic behavior [1,2]. This chaotic behavior has been suggested for several practical applications, including, random number generation (RNG) [2,5], chaotic lidar [6], and secure communication [2,7]. For these applications, the pseudo-random chaotic dynamics generated by the semiconductor with optical feedback is crucial. However, the delay between laser and mirror, essential to trigger chaotic dynamics, also leaves a trace in the laser output. It is known as the Time Delay Signature (TDS); it reveals information about the system and is not desirable in applications. Indeed, for secure communications, the time delay is a crucial parameter that an eavesdropper could exploit [6–9]; for chaotic lidar, the chaotic state should have a flat and smooth spectrum [10]; for RNG, a strong delay signature is synonymous with failing randomness tests [1,2,11]. Suppressing the TDS in laser systems with optical feedback has been demonstrated in several ways: adjusting the injection current [12], adjusting the feedback strength [13], using ring lasers [14], using distributed feedback [15,16], using polarization dependent feedback [17] or adding quantum noise to the system [18] to name a few. One straightforward way to reduce the TDS is achieved by adding a second optical feedback close to the first [19,20]. Overall, adding one delay can either stabilize [21–25] or further destabilize [26–29] the laser depending on the specific configuration. In this case, the feedback system resembles an interferometer, known to be sensitive to phase changes. Indeed, earlier research indicates a feedback phase sensitivity of the dynamics [21,24]. However, a small change in the mirror position, necessary for testing the effect of a change in feedback phase, was not investigated with respect to its impact on the chaotic dynamics in general, or the TDS in particular. The feedback phase sensitivity was researched for stabilizing the system [21,24]. Reference [19] explored the TDS but did not consider subwavelength changes of the mirror positions. In this letter, we show that the feedback phase should be included as a control parameter as it plays a crucial role in the dynamics. Our experiments show that the relative feedback phase has a strong influence on the TDS suppression. First, we measure the threshold

#469410 https://doi.org/10.1364/OPTCON.469410
Journal © 2022 Received 21 Jul 2022; accepted 18 Sep 2022; published 26 Sep 2022

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reduction due to one or two delays when changing the relative feedback phase. This gives an indication that the feedback phase plays a more important role for two delay systems. Second, we study the relation between the relative feedback phase and the TDS suppression and compare it again with the one-delay case. We show that the impact of feedback phase is in the same order of magnitude as optimizing the injection current [12] or feedback strength [13] for the one-delay system. Finally, we also show that the chaotic bandwidth depends on the feedback phase in the two-delay system.

The experimental setup used is shown in Fig. 1. A semiconductor laser is coupled to two mirrors. The laser is a commercially available single-mode edge emitting Distributed FeedBack (DFB) laser (3spTechnologies, 1953LCV1). The laser is kept at a constant temperature of $25°C$. The mirror M1 in feedback loop 1 is on a linear stage (Newport XMS50) which can move in a range of 50 mm with a precision of 1 nm. By changing the position of the linear stage, we can therefore control the position of the mirror at the sub-wavelength scale and thus tune the feedback phase. The other mirror M2 remains fixed. We control the feedback strength in each feedback arm with Neutral Density Filters (NDFs) and the combination of a quarter-wave plate and a linear polarizer. As the light passes twice through the quarter-wave plate, it acts as a half-wave plate, rotating the polarization direction of the input linearly polarized light. By rotating the quarter-wave plate, in combination with the fixed polarizer, we obtain a variable optical attenuator. In this way, we fully control the feedback strength of both arms independently. An optical isolator (Thorlabs IO-5-1550-HP) separates the measurement arm from the rest of the system. The optical spectrum is measured with an optical spectrum analyser with a resolution of 0.08 pm (Aragón Photonics BOSA). A 12 GHz photodiode (12 GHz New Focus 1544-B) is used to measure the time series of the output light with an oscilloscope (12 GHz bandwidth, Agilent DSO81204B). We use the DC bias voltage of the photodiode to measure the overall power of the light. Without feedback, the threshold current is $I_{th} = 21.3$ mA, and the laser emits single mode at 1551.34 nm. Unless stated otherwise, we keep the laser current at 30 mA, so $I = 1.4I_{th}$. At this current, the relaxation oscillation frequency of the laser without feedback is $f_{RO} = 2.25$ GHz or $\tau_{RO} = 1/f_{RO} = 0.44$ ns.

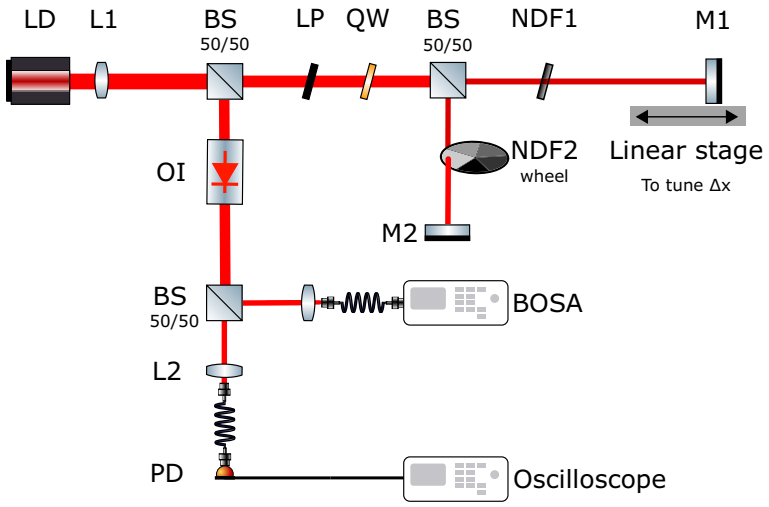


Fig. 1. Experimental setup. LD: Laser Diode, L: Lens, BS: Beam Splitter, LP: Linear Polarizer, QW: Quarter-Wave plate (rotatable), M: Mirror, NDF: Neutral Density Filter, OI: Optical Isolator, PD: photodetector.

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Both mirrors are set approximately at the same distance from the laser cavity. We estimate the delay by measuring the distance between peaks in the RF spectrum of the intensity: for feedback loop 1, this gives $\tau_1 = 3.35$ ns, and for feedback loop 2, $\tau_2 = 3.42$ ns, thus a difference of 0.07 ns, i.e. $0.16\tau_{RO}$. In Ref. [19] it is proposed that for a difference of $0.5\tau_{RO}$ a minimum of the TDS peak is reached. Here the difference is smaller, but we still show strong suppression. In addition we control the feedback phase, which will have a strong impact on the TDS suppresion. We change the mirror position in small increments around τ_1. The total displacement of mirror 1 is 1551 nm, decomposed in 41 identical steps. Therefore, over this range, we tune the relative feedback phase between the feedback arms by 4π (two full periods). We measure the threshold reduction for each arm (blocking the other) to have an indication of the feedback strength through the relative threshold current: $\Delta i = (I_{th} - I)/I_{th}$ with I_{th}, and I the threshold currents without and with feedback, respectively [30]. For the experiment with two delays, the relative threshold reductions are $\Delta i_1 = 0.017$ and $\Delta i_2 = 0.015$, indicating that the feedback strength of loop 2 is slightly lower than in loop 1. We also measure the relative threshold reduction with both feedback arms open for each position of mirror M1 and obtain the results shown in Fig. 2. There is a periodic dependence between the relative threshold reduction and the feedback phase, which suggests that interference is occurring in the feedback loops. Depending on the relative feedback phase, the feedback light can either interfere constructively or destructively. This is a qualitative difference with the one-delay case as such effect cannot occur with a single feedback loop. Indeed, we performed the same experiment for the one-delay case. To isolate the effect of the feedback phase, we adjust the feedback strength so that the same amount of light is fed back inside the laser cavity as in the two-delay case. The determination is based on the threshold reduction. Specifically, by adjusting the NDFs, we set the relative threshold reduction to 0.03, which is close to the sum of the threshold Δi_1 and Δi_2. As shown in Fig. 2, no dependence with respect to the feedback phase is visible.

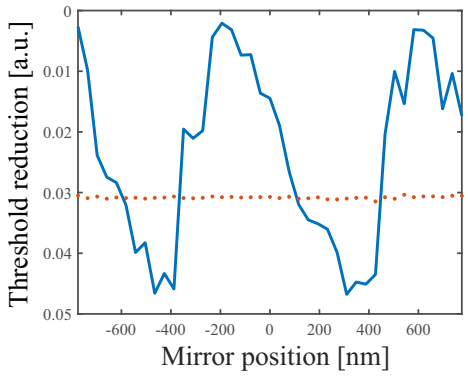


Fig. 2. Relative threshold reduction versus mirror position for one delay (dotted orange) and two delays (continuous blue).

We now turn to the main experiment to investigate the impact of the feedback phase on the TDS. The injection current is 30 mA, all other parameters are the same as in the threshold reduction measurement. Figure 3 shows the results of the experiment with one optical feedback for three different positions of mirror M1, -620 nm, -427 nm, and -233 nm (or in terms of feedback phase: -5.0, -3.5, and -1.9 radians). The time series, RF spectrum (calculated by taking the FFT of the time series), and optical spectrum are shown. Figure 4 shows the same experiment but for the case of double optical feedback. From the time series (Fig. 3 (a_1, b_1, and c_1) and Fig. 4 (a_1, b_1, and c_1) both cases are chaotic for all mirror positions. Moreover, the two cases seem similar based on their time series. Yet, from the RF spectrum, it can be seen that the two-delay case

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is more sensitive to the feedback phase, see Fig. 3 (a_2, b_2, and c_2) and Fig. 4 (a_2, b_2, and c_2). Overall, the RF spectrum is broad and displays peaks separated by approximately $1/\tau_1$. For the one-delay case, changing the mirror position seems to have only a minor impact on the RF spectrum. On the other hand, for the two-delay case, the RF spectrum changes more significantly with the mirror position. In Fig. 4 (a_2) clear peaks appear, which are suppressed when changing the mirror position to -233 nm as in Fig. 4 c_2. When looking at the optical spectrum in Fig. 3 (a_3, b_3, and c_3) and Fig. 4 (a_3, b_3, and c_3), a similar trend occurs though in a more subtle manner than in the RF spectra. The optical spectrum does not change much for the one-delay case, while more significant changes can be observed in the two-delay case, in particular the width of the spectrum.

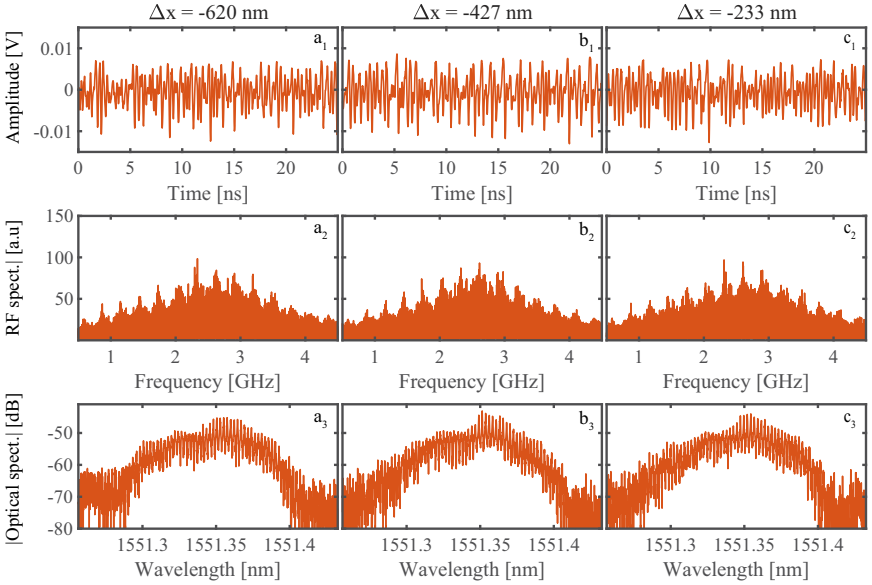


Fig. 3. Laser coupled to a single mirror. From top to bottom: time series, RF spectrum (FFT), and optical spectrum. Each column is for a different position of mirror 1: a) -620 nm, b) -427 nm and c) -233 nm. Changing the mirror position has a limited effect on the laser dynamics.

These results show that the two-delay system dynamics depend more strongly on the feedback phase. To study how this influences the TDS we calculate the autocorrelation function (ACF) ρ and Delayed Mutual Information (DMI) from the time series of the intensity of the laser [31]. Figure 5 shows the ACF and DMI of the one- and two-delay cases for the same three mirror positions as before. For both figures of merit, the height of the peak quantifies the prominence of the TDS. For the one-delay case, only minor changes are visible when the feedback phase is tuned. But for the two-delay case the TDS is clearly impacted. Changing the feedback phase changes the shape, height, and position of the TDS peak. Moreover, for a mirror displacement $\Delta x = -620$ nm (Fig. 5 (a_1 and a_2)), the two-delay case has a more pronounced TDS, while for $\Delta x = -233$ nm (Fig. 5 (c_1 and c_2)), the TDS is more suppressed than for the one-delay case. Moreover, for the two-delay case, both functions display a flat bump around the delay value rather than a sharp peak, making it more difficult to identify accurately the time-delay of the system. The results clearly show that for a semiconductor laser with only one optical feedback, changing the mirror position on this scale does not significantly affect the dynamics. The RF spectrum, optical spectrum, ACF, and DMI are almost unchanged. All observed variations can likely be attributed to noise. However, for the two-delay system, the dynamics depend on the feedback phase.

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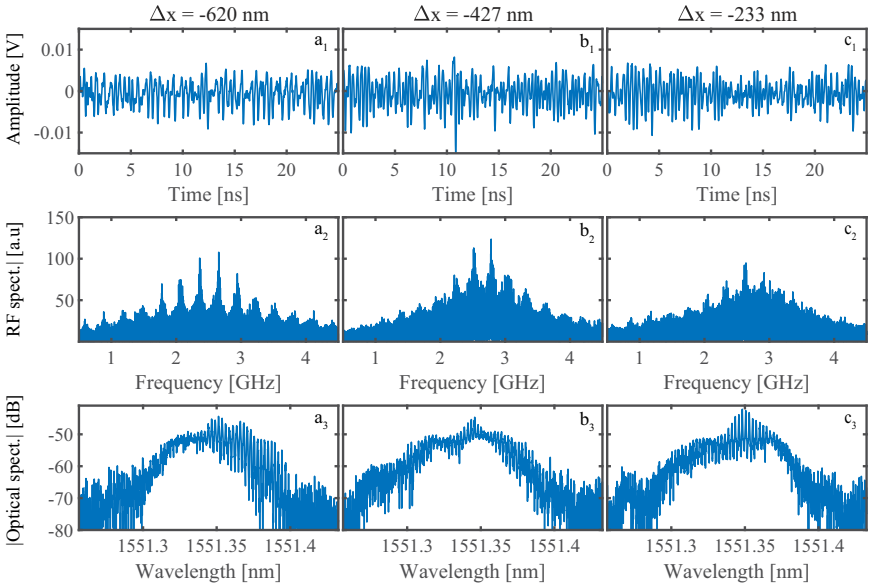


Fig. 4. Laser coupled to two mirrors. From top to bottom: time series, RF spectrum (FFT), and optical spectrum. Each column is for a different position of mirror 1: a) -620 nm, b) -427 nm and c) -233 nm. Changing the mirror position has a stronger effect on the laser dynamics than in the case of a single feedback.

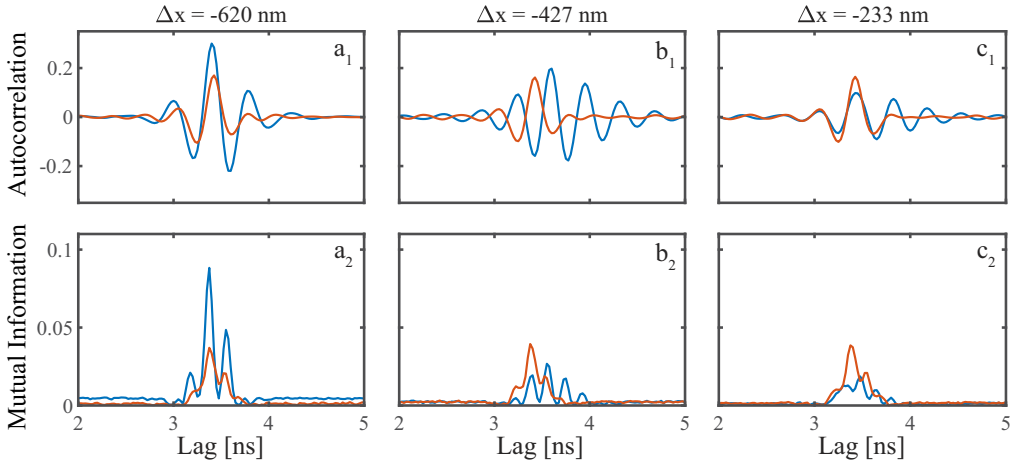


Fig. 5. Comparison of the TDS between the one- (orange) and two-delay cases (blue) for three different mirror position. Top: autocorrelation function. Bottom: delayed mutual information.

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The above results demonstrate that the suppression of the TDS with a second delay at a different time-delay and strength from the first is only feasible when the feedback phase can be controlled. To investigate the effect systematically, we look at the height of the largest peak of the absolute ACF for all the feedback phase steps in the experiment, shown in Fig. 6 (a). For each mirror position, and thus each feedback phase, we calculate the height of the peak in the absolute ACF in a range around the lag where we expect the TDS, specifically in 3.3 ± 1.0 ns. For the two-delay case, the height of the TDS changes significantly. We find a minimum at $\Delta x = 116$ nm with $|\rho| = 0.06$. The maximum is $|\rho| = 0.31$ at $\Delta x = 775$ nm. For the one-delay case, the peak stays around $|\rho| = 0.18$. The DMI shows similar trends. Therefore, we show that the TDS can either be further suppressed or increased by changing the feedback phase. For the sake of completeness, we performed a systematic search in the experimentally achievable parameter space for the case of only one feedback to find the optimal value for the TDS. By changing the current, delay, and feedback strength, the maximum reduction of the TDS corresponds to $|\rho| = 0.15$ in the one delay case. It thus appears that adding a second delay can further suppress the TDS by a factor of almost 3, but, this is only possible with feedback phase control. Our results shed new light on the observations of Ref. [19]. We confirm that a second optical feedback can indeed suppress the TDS more than what can be achieved with only one feedback. However, our results show that the relative feedback phase, associated to small sub-wavelength variations of the mirror positions, has a strong influence on the suppression. For a change of only 200 nm in mirror position, the height of the TDS peak can change significantly, from best to worst suppression. We can therefore conclude that, to use the two-mirror approach to effectively suppress the TDS, the relative feedback phase has to be taken into account and experimentally controlled to avoid significant degradation of the concealment of the TDS.

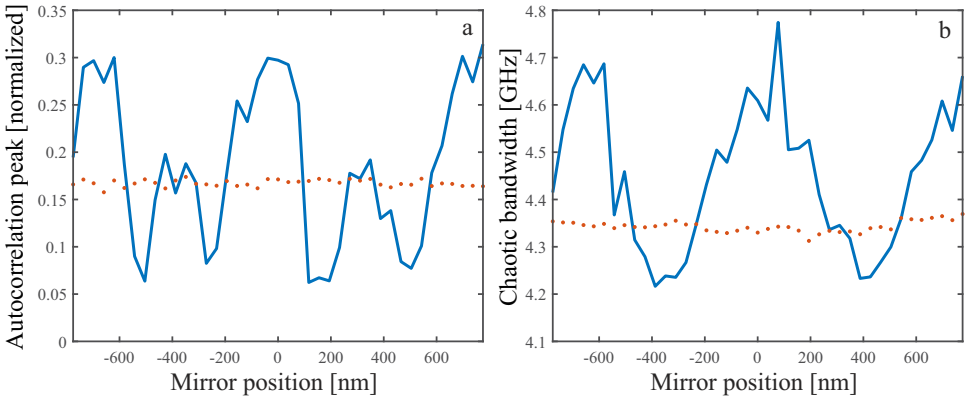


Fig. 6. Comparison of (a) height of the largest peak in the autocorrelation function and (b) chaotic bandwidth for double optical feedback (blue solid) and the equivalent one-delay case (orange dotted).

Besides the effect on the TDS, the RF spectrum also changes when tuning the feedback phase in the two-delay case, as seen in Fig. 4 (a_2, b_2, c_2). To quantify this, we analyse the chaotic bandwidth (CHBW), defined in Ref. [32]. Figure 6 (b) shows how the CHBW changes when changing the feedback phase for both the one- and two-delay cases. Again, for the one-delay case, the CHBW remains almost constant with a value just below 4.4 GHz, while for the two-delay case, there is a clear dependence on the relative feedback phase. The mean value for the two-delay case is 4.45 GHz, higher than the equivalent one-delay value. The maximum value is 4.77 GHz and occurs for $\Delta x = 77$ nm. The comparison of Fig. 6 (a) and (b) shows that the maximum TDS suppression and maximum CHBW do not occur for the same mirror position. For the two-feedback system, there is a trade-off between TDS and CHBW, and one cannot optimize

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them together. However, it is possible to have both a stronger suppression and a higher CHBW compared to the one-delay case, for example, around mirror position 200 nm in Fig. 6. In addition, the gain in TDS suppression is more significant than the loss in CHBW. Specifically, the minimum TDS is 2.5 times smaller than the mean, but the minimum bandwidth is only a few percent lower than the mean. So, although they cannot be optimized together, the CHBW reduction remains minor.

To conclude, we show that the relative feedback phase, corresponding to small subwavelength changes of the mirror positions, is essential to understand the concealment of the time delay in the chaotic dynamics of a semiconductor laser coupled to two optical feedback loops. We demonstrate that the threshold reduction, a measure for the feedback strength, depends on the feedback phase. We confirm that a second delay close to the first, on a scale corresponding to the relaxation oscillation period, can further suppress the TDS compared to the equivalent one-delay case, as shown in Ref. [19]. However, our experiments demonstrate that effective TDS suppression requires control over the feedback phase since changes in the latter over a fraction of the wavelength can modify drastically the quality of the concealment of the time delay value. Controlling the feedback phase in a laser with dual feedback is crucial since it has a strong influence on the feedback strength, the time delay signature and the chaotic bandwidth.

Funding. Fonds Wetenschappelijk Onderzoek (G0E7719N, VS01222N); Vlaamse Overheid (METHUSALEM program); H2020 Marie Skłodowska-Curie Actions (801505); Conseil régional du Grand EstEmbassy of France in Belgium (TOURNESOL program).

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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