Stability Characterisation and Application of Mutually Injection Locked Gain Switched Optical Frequency Combs for Dual Comb Spectroscopy

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***Abstract*—The application of two gain switched optical frequency combs (OFCs) in dual comb gas phase spectroscopy is demonstrated. We report on the stability analysis of the wavelength and power of individual comb lines of the two OFCs. The examination reveals that a maximum wavelength fluctuation of <2.5 pm and a maximum peak power fluctuation of ∼0.3 dB is achievable for the OFCs. The radio frequency (RF) beat tone spectrum shows the standard deviation of the peak power of an individual beat tone from the mean is as low as ∼0.14 dB with negligible frequency fluctuations. In a proof-of-principle experiment the dual comb system is applied to the detection of hydrogen sulphide (H_2S) with a detection sensitivity of (740 ± 160) ppmv, demonstrating its excellent frequency and power stability. The dual OFCs can in principle be monolithically integrated and thus enable the development of compact, cost-efficient dual comb devices, for the detection of multiple trace gas species or isotopologues.**

***Index Terms*—Gain-switched laser, gas detection, hydrogen sulphide, optical frequency comb, optical injection locking, semiconductor lasers, trace gas sensing.**

I. Introduction

In RECENT decades, optical frequency combs (OFCs), providing a number of equally spaced, phase coherent narrow spectral lines, have been used in state-of-the-art gas-phase laser (absorption) spectroscopy [1]. Typical OFCs employed for this purpose have been based mainly on semiconductor and fibre mode-locked lasers [1]. However, these techniques suffer from costly and complex fabrication processes and an inherently fixed free spectral range (FSR). While electro-optic modulators may be seen as a viable alternative offering tuneable FSR [2], [3], they can suffer from bias drift causing instability, which may require additional feedback-based dc bias control to maintain stable operation [4]. Kerr effect-based micro-ring resonators can be used but these combs require a pumping scheme which typically needs a pump power of at least a few tens of milliwatts [5]. Gain switching of commercially available semiconductor lasers to generate an OFC has gained interest due to its simplicity (direct modulation) and flexibility (wavelength and FSR) [6]. Some shortcomings associated with gain switching can be overcome by external optical injection locking (OIL) realised via a primary-secondary configuration [7]. External OIL can enhance the OFC by improving the number of generated comb lines, the spectral flatness, and the transferring of the primary laser's narrow linewidth to each individual comb line [7].

In recent years, dual comb spectroscopy (DCS) [8], [9] has become a popular approach to overcome many of the constraints of conventional Fourier transform spectroscopy. DCS simplifies the receiver and offers high precision, short acquisition times and potentially low bandwidth detectors [8], [10]. DCS uses a pair of OFCs with small differences in their respective FSRs. When the tones of both OFCs beat on a photodetector, an RF beat spectrum is generated; the intensity variations (absorption of comb lines) are translated into an RF beat spectrum. Crucial factors for DCS are high frequency accuracy and high spectral resolution [11]. In this letter, it is described how high frequency accuracy and high resolution can be provided through a high level of phase coherence between two gain switched OFCs. The two gain switched OFCs can be generated using cost-efficient commercially available semiconductor lasers. The OFCs are phase and FSR locked via external optical injection with a single semiconductor tuneable laser (TL). The mutual injection locking of the two OFCs results in a narrow linewidth RF beat tone spectrum stable in both frequency and amplitude. Two of the main parameters governing the overall stability of the individual OFCs, and in turn the stability of the generated RF beat tone spectra, are the variations in optical power and the wavelength of the individual comb lines with respect to time.

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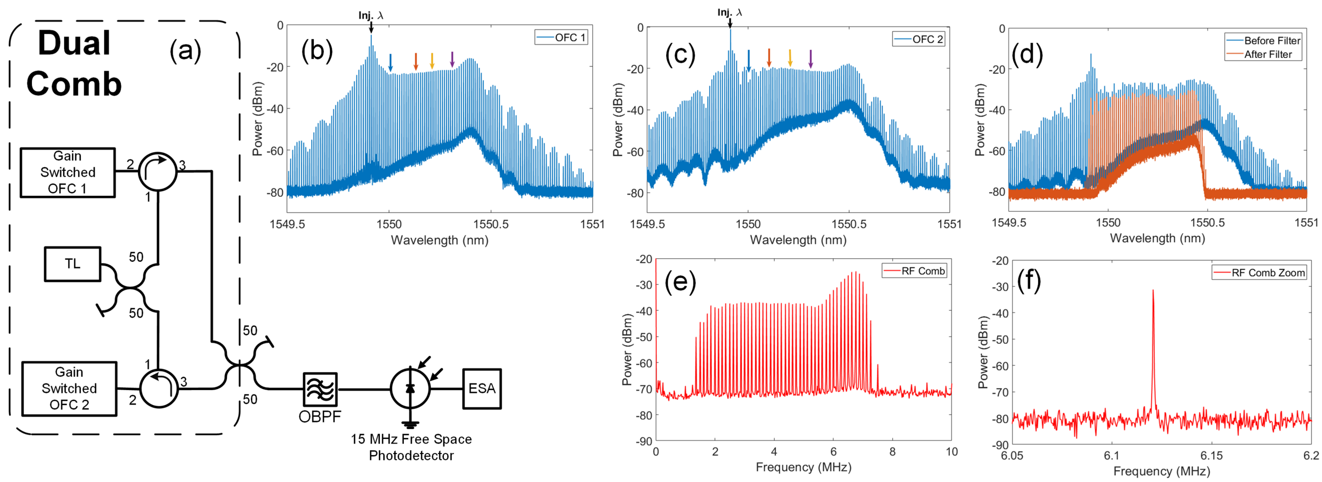

Fig. 1. (a) Dual comb system based on mutually injected gain switched OFCs. Optical spectra of (b) OFC1 and (c) OFC2 prior to coupling; the vertical coloured arrows in (b) and (c) Indicate the comb lines used in the stability analysis, and the black vertical arrow indicates the injection wavelength; (d) Dual comb before (blue) and after (orange) the OBPF. All optical spectra are measured with a resolution of 0.16 pm. Electrical spectrum of (e) the corresponding RF beat tones with a resolution bandwidth (RBW) of 100 Hz; (f) Measurement of a single RF beat tone with an RBW of 10 Hz. OFC: Optical frequency comb; TL: Tuneable laser; OBPF: Optical bandpass filter; ESA: Electrical spectrum analyser.

In this paper, the stability of the individual mutually injection locked OFCs is characterised in terms of wavelength and power fluctuations. A characterisation of the generated RF beat tone spectrum is then conducted examining the relative frequency fluctuations and peak amplitudes of individual RF tones. Finally, the applicability of this dual comb system for gas absorption spectroscopy is demonstrated through the detection of H_2S in a 661 cm single pass cell. This offers detection below the lower explosive limit. It is important to note that the dual comb system outlined in this paper lends itself to being monolithically integrated, enabling the realisation of a compact and cost-efficient dual comb interrogator which should provide even greater wavelength and amplitude stability [12].

II. Experimental Setup

The dual comb system used in this work is shown in Fig. 1(a). It comprises two Fabry-Pérot (FP) lasers, acting as secondary lasers in a dual primary-secondary configuration, with thresholds of 12 and 13 mA respectively. The FP lasers are biased at 17.5 and 25.9 mA respectively with their corresponding temperatures being maintained at 23.2 and 31.6 °C. Utilising these FP lasers allow for central wavelength tuneable dual comb generation across the entire C-band (∼1525 – 1575 nm) [6]. Both FPs are gain switched [7] using sine waves, amplified to ∼24 dBm, at frequencies of 1.250000 and 1.250125 GHz, respectively. The individual OFCs are mutually injection locked using a single TL acting as a common primary laser providing phase synchronisation between both secondary lasers. The wavelength of the primary laser (injection wavelength), is optimised to 1549.901 nm, as indicated by the black arrow in Fig. 1(b) and (c). The TL is detuned to a lower wavelength of the individual OFCs, allowing for the creation of broad asymmetric OFCs [6]. Utilising asymmetric OFCs will maximise the number of comb lines, generating unique RF beat tones at wavelengths higher than the injection wavelength [13]. The optical spectra of the generated mutually injection locked OFCs are observed, using a high-resolution optical spectrum analyser (HR-OSA) with a resolution of 0.16 pm. The respective spectra for OFC1 and OFC2 are shown in Fig. 1(b) and (c). The two OFCs are combined using a 3-dB coupler. It is important to note that all individual fibres and components used in this experiment prior to the wavelength and bandwidth tuneable optical bandpass filter (OBPF) (EXFO XTM-50) are polarisation maintaining. The dual comb before the OBPF is shown by the blue line in Fig. 1(d). The OBPF is used to remove the comb line where the injection occurs and the tones lower than the injection wavelength (≤1549.901 nm). The resulting output from the OBPF is shown by the orange line in Fig. 1(d). The OBPF ensures that any beating on the photodetector between the two OFCs will generate a unique RF beat tone frequency. The filtered dual comb is subsequently sent to a 15 MHz InGaAs photodetector. The tones from the dual comb yield an RF comb spectrum with 125 kHz harmonics. The RF comb spectrum, shown in Fig. 1(e) by the red trace, is captured on an electrical spectrum analyser (ESA). A resolution bandwidth (RBW) of 100 Hz was used. An ESA is used as we did not have access to a real time oscilloscope. A measurement of a single RF beat tone is shown in Fig. 1(f), with an RBW of 10 Hz, illustrating the narrow RF linewidth achieved as a result of the beating of the correlated OFCs.

III. Stability Analysis

Initial stability tests are performed on the individual OFCs utilising the HR-OSA. The optical spectra were captured every ∼5 s over a 60 min period at the output of the individual OFCs but before the 50/50 coupler in Fig. 1(a). Wavelength and peak power stability analysis is performed simultaneously for each comb line of the individual OFCs. Fig. 2(a) and (b) illustrate the relative wavelength fluctuations of four comb lines belonging

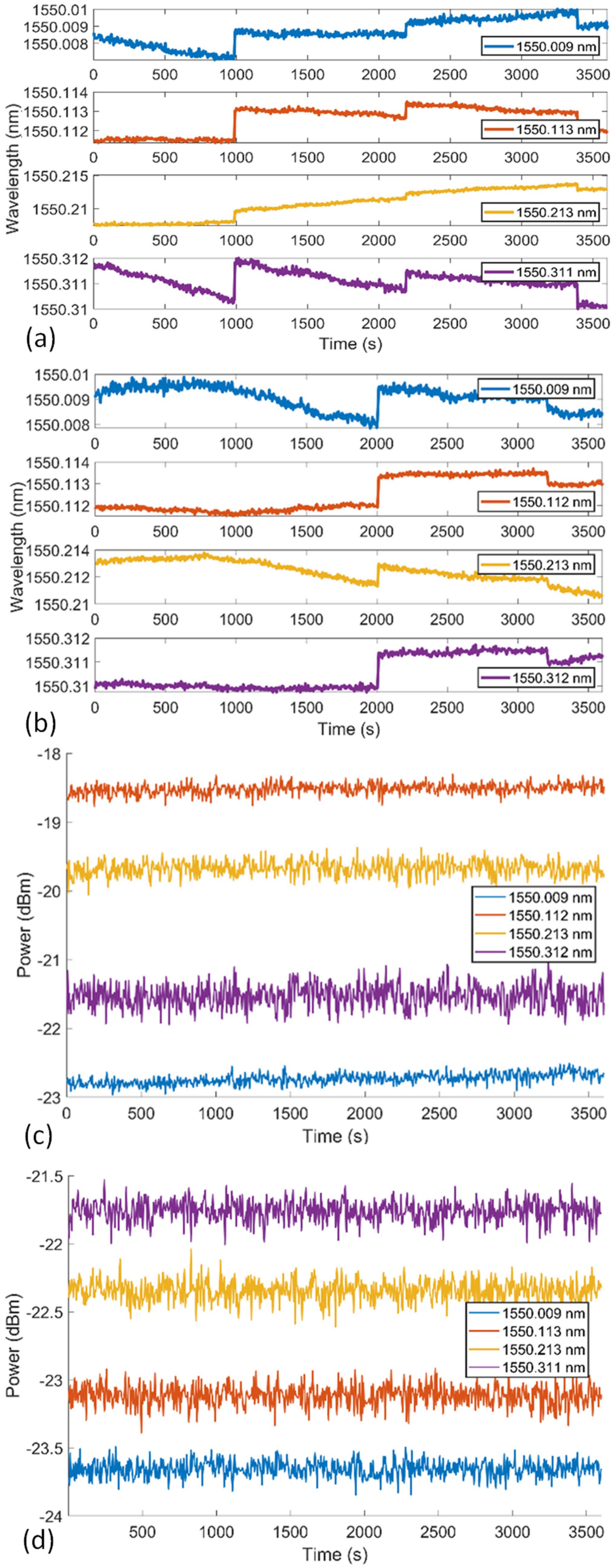

Fig. 2. Relative wavelength (nm) vs time (s) of four comb lines from: (a) OFC1 and (b) OFC2. Peak power (dBm) vs time (s) of four comb lines from: (a) OFC1 and (b) OFC2. The selected comb lines are indicated by arrows in Fig. 1(b) and (c), respectively.

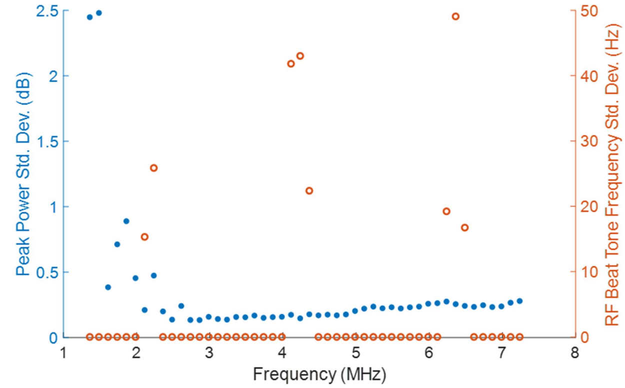

Fig. 3. Standard deviation of the peak amplitude (blue circles) and standard deviation of the RF beat tone frequency (orange circles) for each tone of the RF spectrum at its individual RF beat tone frequency. 42 samples were captured every 11 s over a ∼60 min period.

to each OFC at the wavelengths indicated by the corresponding coloured arrows in Fig. 1(b) and (c), respectively. A high degree of robustness is observed with a maximum wavelength fluctuation of <2 pm, without the need for complicated automated feedback control. Fig. 2(c) and (d) illustrate the peak power fluctuations of four comb lines belonging to OFC1 and OFC2 at the wavelengths indicated by the corresponding coloured arrows in Fig. 1(b) and (c), respectively [14]. Examining the peak power stability in Fig. 2(c), it is evident that the maximum fluctuation of the comb line at 1550.312 nm is ∼0.3 dB, indicated by the purple line. The power fluctuations increase with increasing wavelengths, i.e., further away from the injection wavelength. Inspecting the peak power stability of OFC2 (Fig. 2(d)) shows that the comb line at the longest wavelength (purple trace) exhibits the largest variation. At this wavelength the maximum fluctuation is ∼0.25 dB. Note, that these results are limited by a power resolution of 0.2 dB of the HR-OSA, and that each OFC is measured at different times as we only have access to one HR-OSA.

Subsequent to the optical stability tests, the RF beat tone spectrum was characterised in terms of individual RF beat tone peak power and frequency stability. The peak power and frequency of the individual RF beat tones of the generated RF beat tone spectrum were monitored over ∼60 min and recorded at intervals of 11 s. The maximum frequency fluctuation for any one tone was <1 kHz and the standard deviation is <50 Hz, as shown in Fig. 3. The standard deviation of the RF beat tone peak power was calculated and is shown in Fig. 3. The larger standard deviation experienced by the first RF beat tones can be attributed to being on the edge of the OBPF passband. It is also evident that as the RF frequency increases, the peak power standard deviation exhibits a marginal increase with a final value of ∼0.28 dB for the last RF beat tone. This is a result of the greater amplitude fluctuations of the individual OFCs, as the wavelength increases further away from the injection wavelength. Despite this, 41 samples showed very stable behaviour in frequency with a peak power standard deviation smaller than 0.3 dB established without any averaging or additional digital signal processing.

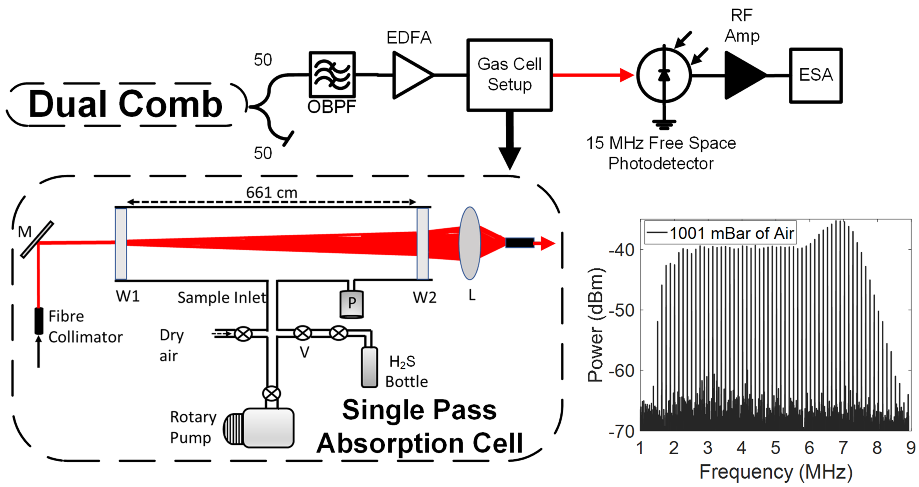

Fig. 4. Measurement set up of dual comb-based gas sensing using a single pass cell with a resulting RF spectrum placed inset.

IV. Spectroscopy Application

Finally, the wavelength tuneable dual comb system was utilised to measure the absorption of H_2S in synthetic air close to standard pressure at a wavelength of ~1574.55 nm. Utilising the TL, it was possible to inject into the modes of FP lasers at 1574.376 nm to generate mutually injected OFCs. The optical spectrum is not shown here as it is outside the wavelength range of the HR-OSA. The OFCs possessed FSRs of 1.250000 and 1.250125 GHz. The signal from the OBPF is approximately −15 dBm and is amplified by an Erbium doped fibre amplifier (EDFA) to 0 dBm.

A single pass static gas cell with a length of 661 cm was used for this application. The light beam from the dual comb was collimated (Thorlabs F260APC-1550) and guided to a cylindrical stainless steel cell (100 mm diameter) with quartz windows (diameter 25 mm) at either end, acting as optical ports. Before experiments, the cell was always evacuated by a rotary pump to < 0.1 mbar. The light exiting this single pass cell was collected by an achromatic lens and focused onto the active area of a fast photodiode. The photodiode was attached to the ESA to capture the electrical beat spectrum. Measurements were carried out by first filling dry air at approximately atmospheric pressure (1007.0 mbar) into the evacuated gas cell, in order to measure the transmission, I_0, without the sample species. The gas cell was evacuated after the I_0 measurements again and a small amount of H_2S (15.8 mbar) was gradually injected into the chamber. After a waiting time of 10 min the cell was topped up with 991.2 mbar of dry air so that the total pressure was again ~1007.0 mbar.

The transmission, I, with sample (H_2S) under quasi atmospheric conditions was recorded after an additional waiting time of 20 min. The absorption coefficient as a function of wavelength, $\alpha(\lambda)$, of H_2S was calculated using the Beer-Lambert law (see (1) below) for the approximation of small optical losses:

$$\alpha(\lambda) = n\sigma(\lambda) = \left(\frac{I_0(\lambda)}{I(\lambda)} - 1\right)\frac{1}{d} \tag{1}$$

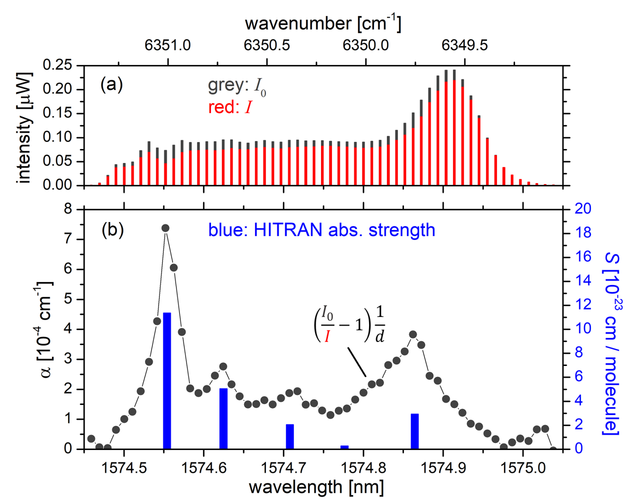

Fig. 5. (a) Comb intensities transmitted through the gas cell (length $d = 661$ cm) filled with H_2S and air (I, red) and air only (I_0, black). (b) Spectrum of the absorption coefficient, $\alpha = d^{-1}$ [(I_0/I)-1] (resolution 0.04 cm^{-1} according to FSR of 1.25000 GHz) and stick spectrum (blue) of the absorption strength, S, from the HITRAN database [16].

Here n is the number density of H_2S, $\sigma(\lambda)$ is the wavelength-dependent absorption cross-section of H_2S, and d is the interaction pathlength (distance between the quartz windows) [15]. Fig. 5(a) shows the transmitted relative comb intensities corresponding to measurements of I_0 (grey trace) and I (red trace). The drop in intensity between the red and black traces is clearly discernible. The spectrum of the absorption coefficients (black dots) is shown in Fig. 5(b) along with the integrated absorption strengths, S, for H_2S from the HITRAN database [16]. The half-width of the band at ~1574.55 nm is covered by approximately four comb tones. The wavelength scale in Fig. 5 is based on the calibrated and stable emission wavelength of the master laser. The wavelength accuracy is further corroborated through Fig. 5(b) by comparing the line positions reported in HITRAN data base, which are in good agreement in the region shown.

The overall measurement time for the H_2S measurements was below 60 min and the comb was stable within the limits outlined in Section III during this time. The minimum detectable absorption coefficient can be calculated from the standard deviation, σ, of the noise of the detected intensities [17]. 1σ of the linear dual comb intensities achieved was 0.0093 ($\sim$0.01). Substituting this value into (1) yields a minimum estimated α of 1.4×10^{-5} cm^{-1}. The approximate absorption cross-section for the line at 1574.55 nm for the given measurement conditions at 1007 mbar and room temperature is 7.587×10^{-22} cm^2. From the minimum absorption coefficient and cross-section, the minimum detectable number density can be estimated to be $\sim$740 ppmv. The major uncertainty contributing to the measured number densities of H_2S is dominated by the uncertainty in the absorption cross-section and self-broadening parameters in the HITRAN database [16]. This overall uncertainty is approximately 22%. Other minor uncertainties are based on the measurement error of $\sim$0.2% of the absorption pathlength, and the comb intensity fluctuations of $\sim$1%. The total detection sensitivity based on Gaussian error propagation in this proof-of-principle experiment was therefore (740 $\pm$ 160) ppmv [18].

V. Conclusion

The work in this paper illustrates the importance of mutually injection locking both OFCs to obtain relative wavelength stability and a high degree of phase correlation. Minimisation of the power fluctuation to $\sim$0.3 dB has been achieved for individual OFC lines, highlighting the importance of a stable RF source. The power fluctuation of the dual comb system outlined here could potentially be minimized further through photonic integration of the interrogator [12]. The maximum wavelength fluctuation of any individual comb line is measured to be $\sim$2.5 pm. In turn, this generates an RF comb comprising 41 sample points with a peak power standard $<$0.3 dB and a frequency stability within 1 kHz. The applicability of this dual comb system for gas absorption spectroscopy is demonstrated through the detection of H_2S where a sensitivity of 740 $\pm$ 160 ppmv is achieved in a 661 cm single pass gas cell, which allows for detection below the lower explosive limit. Through photonic integration of the dual comb system and utilization of stable RF sources, the stability of the RF beat tone spectrum could be improved significantly further and enable greater sensitivities to be achieved. In conclusion, these measurements highlight the robustness of a potentially monolithically integrable and cost-efficient dual comb system, which provides mutual coherence between two OFCs and offers excellent stability without the requirement for automated or complex electrical or optical feedback control or manual adjustments.

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