LASER PHASE NOISE REJECTION BY TWO-WAVE MIXING PHOTOREFRACTIVE INTERFEROMETRY

M. Dubois [1] and T. E. Drake [2]
[1]General Electric Global Research, Schenectady, NY, USA;
[2]Lockheed Martin Aeronautics Co., Fort Worth, TX, USA

Abstract: Laser-ultrasound is a technique currently used for the ultrasonic inspection of composites during manufacturing of advanced jet fighters. This technique is based on a short-pulse laser to generate ultrasonic waves and a long-pulse laser coupled to an interferometer to detect the resulting displacements. In theory, the signal-to-noise ratio of the signal is proportional to the square root of the collected detection light power. In practice however, noise from the laser limits the signal-to-noise ratio above a certain collected power level. When using conventional Fabry-Perot interferometers to demodulate ultrasonic information, one type of noise, amplitude relaxation noise, can be rejected using a differential configuration based on two cavities stabilized on opposite sides of the resonance peak. Another type of laser noise, phase noise, cannot be rejected using Fabry-Perot interferometers and currently limits signal-to-noise ratio. A new type of interferometer based on a photorefractive crystal can be made almost completely insensitive by matching the optical path lengths of the pump and signal beams while still rejecting amplitude noise. In this paper, the phase noise rejection capability of a commercial two-wave mixing photorefractive interferometer is experimentally demonstrated. Results will be presented that demonstrate that speckle effect is not an issue for composite inspection using this interferometer and that it can operate in the photon statistics noise regime for higher collected light powers than conventional differential Fabry-Perot systems.

Introduction: A new technique called laser-ultrasound has been developed since the beginning of the 1980's for the ultrasonic inspection of composite parts in the aircraft industry. This technique is more than an order of magnitude faster than conventional techniques based on piezoelectric transducers and water jets for the non-destructive inspection of complex-shape composite parts during manufacturing.[1] Laser-ultrasound is based on a short pulse laser that generates ultrasonic waves by thermal expansion and on a second long-pulse laser coupled to an interferometer that detects the corresponding mechanical displacements.[2] The laser-ultrasound technology developed at Lockheed Martin Aeronautics Co. and named LaserUT™ is the inspection method for more than 90% of the composite parts of the F/A-22 and will also be used for the F-35 production, to begin in the next few years, resulting in hundreds of millions of dollars in savings.

One disadvantage of the laser-ultrasound technology compared to conventional ultrasonic techniques is the lower sensitivity. For most current applications, sensitivity is satisfactory but for some challenging cases, higher sensitivity is required. For those special cases, sensitivity needs to be improved. Sensitivity is characterized through the signal-to-noise ratio (SNR). The SNR of a Fabry-Perot interferometer used for laser-ultrasound composite inspection can be expressed in the following form:[3]

$$SNR = KSU\sqrt{\frac{P_{\det}\eta}{\lambda B}} \tag{1}$$

where S is the interferometer sensitivity, U is the ultrasonic displacement, $P_{\det}$ is the collected detection light, η is the detector quantum efficiency, λ is the optical wavelength, B is the detection bandwidth, and K is a constant

According to equation (1), there are a limited number of parameters through which SNR can be increased. From those, S is theoretically limited to 1 and the efforts spent in the last twenty years to develop better interferometers for laser-ultrasound applications[2-5] resulted in interferometers close to that limit. Detector quantum efficiency is already better than 50% and bandwidth is fixed by the nature of the materials and the type of defects to be detected. A shorter optical wavelength does not provide any advantage because of the current state of laser and detector technologies.

Of the two remaining parameters, *U* can be increased by improving ultrasound generation. This parameter is particularly interesting because as shown in (1) SNR increases linearly with *U*. Generated ultrasonic amplitude is directly proportional to the absorbed laser energy and is therefore limited by the damage threshold of the inspected part. However, laser generation mechanisms of ultrasonic waves have been recently studied and optimized generation laser parameters have been found,[6,7] improving ultrasound generation for the same absorbed laser energy. Some of these improvements have been implemented into the LaserUT inspection system, resulting in important improvements in sensitivity. Despite this significant gain, new challenging parts make LaserUT always hungry for more sensitivity.

The last parameter to increase sensitivity is the collected light, P_{det}. Equation (1) shows that SNR should improve as the square root of the collected light power. Collected light can be increased in several ways: larger collection optics, higher power detection laser, shorter detector-sample distance, or any combination of those. In practice however, Equation (1) does not take any laser noise into account, which limits the SNR above some collected light powers. To minimize this noise source, LaserUT systems use the most stable and quiet single-frequency lasers commercially available, non-planar ring oscillators (NPRO),[8] as master oscillators in a master-oscillator-power-amplification (MOPA) configuration for detection lasers. The NPRO manufacturers claim coherence lengths exceeding 1 km and frequency widths of less than 5 kHz.[9] Even in those very quiet lasers, two types of noise limit the SNR. The first laser noise to appear is amplitude noise. Differential detectors, like the ones in the dual-cavity Fabry-Perot interferometers used by LaserUT systems, can significantly reduce amplitude noise. Amplitude noise rejection is obtained by stabilizing the two cavities on opposite sides of the resonance peaks. The resulting response to ultrasonic phase modulation is therefore opposite and subtraction of the two detectors rejects amplitude noise. Once amplitude noise has been significantly reduced, SNR increases nearly as the square root of the collected light until a different laser noise appears: phase noise. SNR is then limited by phase noise. These SNR limitations are illustrated in Figure 1 where SNR is plotted as a function of collected light power for single-cavity and dual-cavity Fabry-Perot interferometers. Figure 1 also plots the calculated curve of SNR increasing as the square root of the collected light power.

Figure 1 shows that SNR is limited to approximately 26 dB for a single-cavity Fabry-Perot above 1 mW. With a dual-cavity Fabry-Perot, amplitude noise is rejected and SNR reaches approximately 45 dB at 10 mW of collected light. Above that value, SNR for the dual cavity departs from equation (1) to remain approximately flat for higher collected light powers. SNR is then limited by phase noise in the detection laser. LaserUT systems have been designed with this limitation in mind, leading to collected light powers below 10 mW.

Figure 1 demonstrates the advantage of amplitude noise rejection. For collected light powers above 10 mW, the gain in SNR is nearly 20 dB over a single-cavity Fabry-Perot. Additional gains in SNR are possible if phase noise effects were rejected. In this paper, phase noise rejection is demonstrated using a two-wave mixing photorefractive interferometer.

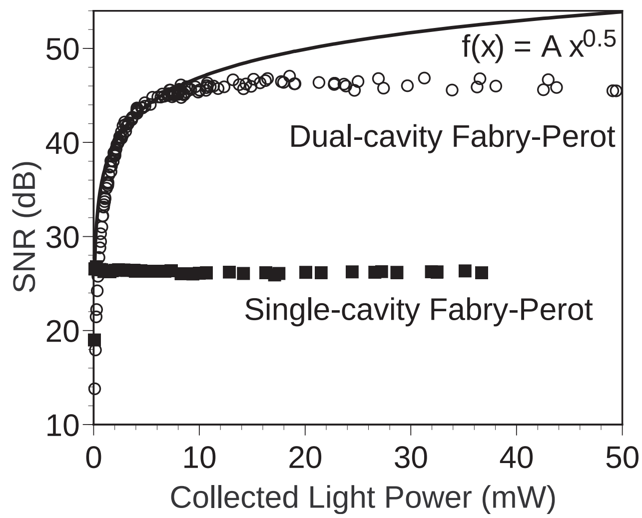


Figure 1 Experimental SNR data as a function of collected light power for a dual-cavity Fabry-Perot in transmission (open circle) and a single-cavity (squares) Fabry-Perot in transmission. The continuous curve is the theoretical SNR as predicted by equation (1).

Results: A new type of reference beam interferometer using photorefractive crystals has been developed in recent years for laser-ultrasound applications.[4,10] The two-wave mixing phenomenon in the photorefractive crystal makes the reference beam phase front match the signal beam phase front reflected off the sample, giving a large etendue to the interferometer. The amplitude laser noise rejection by the two-wave-mixing interferometer using a differential detector has been demonstrated and in theory, the interferometer can also reject phase noise when the optical path lengths of the signal and reference beams are matched.[11] In comparison with confocal Fabry-Perot interferometers, the two-wave mixing photorefractive interferometer is also more compact, is less sensitive to ambient vibrations, does not require active stabilization, and presents almost as good sensitivity in the frequency range of interest for composite inspection.[12] However, the two-wave mixing photorefractive interferometer presents two major disadvantages: it is sensitive to a speckle effect associated with movement of the detection laser spot on a rough surface and it is also sensitive to the Doppler effect caused by the relative target displacement along the line of sight of the detection laser beam. These two disadvantages might make the two-wave mixing interferometer useless for the inspection of composite for the aeronautic industry. A scheme has been proposed to compensate for the Doppler effect and the speckle effect was found two orders of magnitude lower than the Doppler effects, making the speckle effect possibly negligible for the proposed applications.[13] On one hand, the proposed scheme to compensate for the Doppler effect still remains to be tested during an actual composite inspection but is believed to provide a workable solution to the problem. On the other hand, the speckle effect might be different for different samples due to variations in surface roughness and for different response times of the photorefractive crystals.

The speckle effect on the sensitivity of the two-wave mixing photorefractive interferometer (a TWM-1000 based on an iron-doped InP crystal from Tecnar-Automation ltd) was tested using a sample made of a typical 6-mm thick polymer fiber composite laminate. Sample was flat and cut as a disk 30 cm in diameter. Three screw holes were machined into the composite disk to bolt it to a 6.25-mm thick aluminum disk having a diameter of 20 cm. The laminate disk was centered on the aluminum disk that was used to ensure the flatness of the composite part in order to reduce to a minimum the Doppler effect. Sensitivity was measured using an actual ultrasonic signal generated by a 3.2-µm wavelength pulsed source instead of using a phase modulator. The ultrasonic signal was detected on the rough side of the laminate, opposite to the smooth moulding tool side, just outside the edge of the aluminum disk. The detection laser was a long pulse

Nd:YAG laser having a peak power of 500 W of which 150 W was used to pump the InP:Fe crystal. Linear speed was calculated by multiplying the angular velocity of the disks by the distance of the center of the 5-mm detection spot from the centers of the disks. The amplitude of the ultrasonic echo as a function of linear speed is plotted in figure 2.

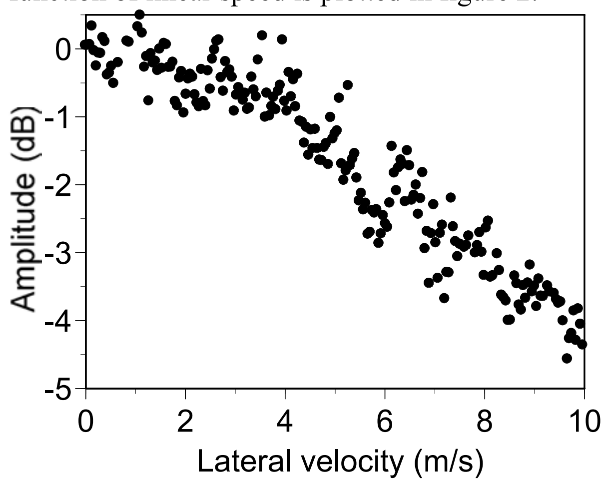


Figure 2 Amplitude of laser-generated ultrasonic echo detected on the rough side of a composite laminate disk by a two-wave mixing photorefractive interferometer as a function of lateral velocity. Error is estimated to be approximately ±0.5 dB, as indicated by the measurement point distribution.

Figure 2 shows that up to approximately 3 m/s, the amplitude of the signal did not change significantly. Above 3 m/s, amplitude dropped continuously to –4 dB at 10 m/s. It is not clear if some remaining Doppler effect due to slight misalignment or sample fluttering, or the actual speckle effect caused the signal drop. In any case, the current maximum lateral velocity in LaserUT inspections is 0.8 m/s (2 mm steps at 400 Hz) and future development should bring lateral velocity to 2 m/s (2 mm steps at 1 kHz). Figure 2 indicates that the speckle effect should not be a concern at those speeds if a two-wave mixing photorefractive interferometer were used, opening the door to signal quality improvement through phase noise rejection, assuming that the scheme proposed to compensate for the Doppler shift[13] will be effective.

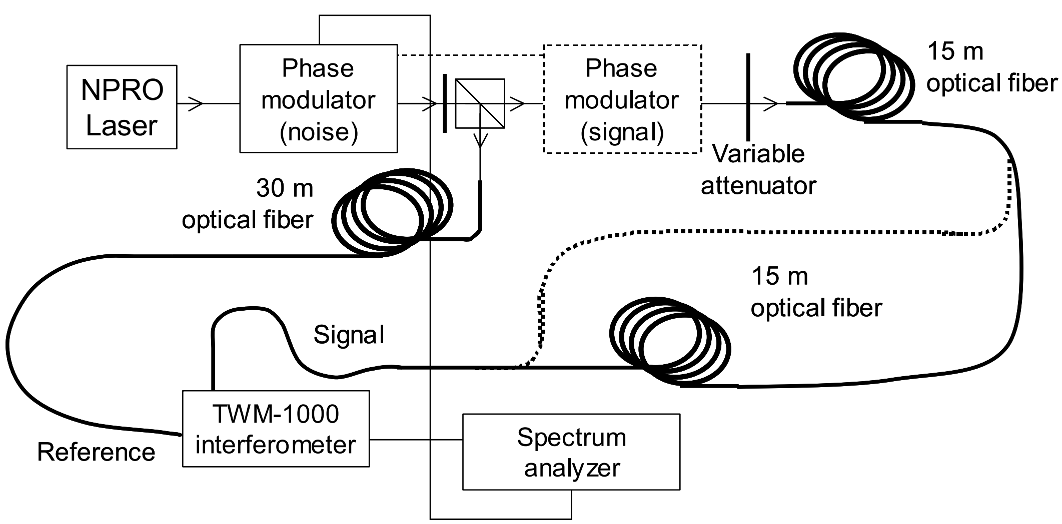


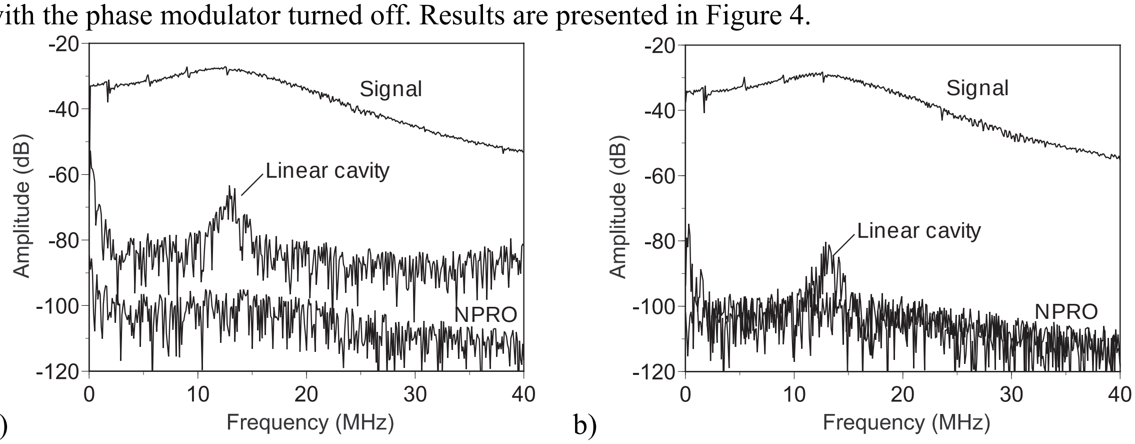
Figure 3 Sketch of the experimental setup to test phase noise rejection by the TWM-1000 interferometer. The phase modulator was positioned either before the beamsplitter (noise position) or after the beamsplitter (signal position). The length of the optical fiber bringing the reference beam to the interferometer had a fixed length of 30 m whereas the total length of the optical fiber bringing the signal beam to the interferometer was either 15 m or 30 m.

The experimental setup used to test phase noise rejection by a two-wave mixing photorefractive interferometer is sketched in Figure 3. Two different detection lasers were used. One laser was a single-longitudinal-mode diode-pumped NPRO, a 1.5 W Mephisto from Innolight, having a coherence length exceeding 1 km.[8, 9] The other laser was a 500-mW single-longitudinal-mode diode-pumped linear-cavity laser from Crystalaser® having a nominal coherence length of 100 m. Both lasers operated at a wavelength of 1064 nm and the cost of the NPRO laser was approximately three times the cost of the linear cavity laser per power unit.

The laser beam was separated into reference and signal beams using a half waveplate and a polarizing beamsplitter. A single electro-optic phase modulator (New Focus 4004) was placed in the laser beam path either before the beamsplitter, where the modulator simulated phase noise (noise position), or after the beamsplitter, in the signal beam path, where the modulator simulated signal (signal position). The reference and signal beams were sent to the two-wave mixing interferometer through optical fibers. The optical fiber for the reference beam had a fixed length of 30 m whereas the optical fiber for the signal beam had a total length of either 15 m or 30 m. With the signal beam having a 30 m length, the optical paths of the reference and signal beams were the same to within 1 m. A variable neutral density attenuator controlled the signal power sent into the interferometer.

The output signal of the interferometer was obtained as a function of modulation frequency using a spectrum analyzer. The same spectrum analyzer drove the electro-optic phase modulator with a 1V amplitude signal.

Signal curves as a function of frequency were obtained with the phase modulator in the signal position for the two different lengths of signal optical fiber and for the two lasers. A few mW of power was sent in the signal optical fiber and approximately 400 mW in the reference optical fiber. Noise curves were obtained using the same operating conditions as for the signal curves but with the phase modulator turned off. Results are presented in Figure 4.



a) b)

Figure 4 Signal (upper curve) and noise (lower curves) at the output of the TWM-1000 interferometer with the NPRO and linear cavity lasers with difference in optical path lengths between the reference and signal beams of a) 15 m, b) 0 m. Only one signal curve is shown in both graphs because signal curves are nearly identical for both lasers.

Figure 4 a) corresponds to the case of a 15 m difference in path length between reference and probe beams. That figure shows that the propagation delay between the reference and signal beams introduced by the 15-m difference generates approximately 20 dB more noise for the linear cavity laser than for the NPRO. This noise is related to the coherence length of the lasers and is called phase noise. However, if the path lengths of the reference and signal beams are the same, the absence of propagation difference makes the system less sensitive to phase noise. This situation is illustrated in Figure 4 b) which shows the experimental results for the case where the fibers for the reference and signal beams have the same lengths. In this figure, both noise curves are at the same levels, except around 12 MHz where the linear cavity laser exhibits a 15 dB noise peak related to residual relaxation amplitude noise not rejected by the differential detector. Using the same path length (within 1 m) for both beams improved the SNR by 20dB for the linear cavity laser. If signal around 12 MHz is of no interest (in most composite inspection, only signal in the 1-10 MHz is of interest), both lasers produced very similar SNRs. It is interesting to notice that the noise level of the NPRO did not change significantly between Figure 4 a) and Figure 4 b), confirming that the coherence length of the NPRO laser is much longer than 15 m.

In a follow-up experiment using the experimental setup sketched in Figure 3, the phase modulator was put in the noise position. Using experimental conditions similar to those given in the previously described experiment along with the NPRO laser, signals were obtained with the phase modulator still driven by the spectrum analyzer for path length differences of 0 m and 15 m between the reference and signal beams. The experimental curves are presented in Figure 5.

This experiment corresponds to the case where a modulated phase noise is present in the laser. This situation can be modeled by adding phase noise terms and a constant phase term to an equation for the signal beam amplitude E_d transmitted through a photorefractive crystal for ultrasound detection.[4] The constant phase term, δ, represents the phase difference introduced by a difference in the propagation lengths of the signal and reference beams. The modified equation now takes here the following form:

$$E_d(x,t) = e^{-\alpha x/2} E_d(0,0)\left[(e^{\gamma x} - 1)e^{iA\sin(\omega t+\delta)} + e^{i\varphi(t)+iA\sin(\omega t)}\right] \quad (2)$$

where A is the amplitude of phase noise, ω is the angular frequency of phase noise, and t is time. $\delta = \omega nL/C$, where L is the path length difference, n is the refractive index of propagation medium (optical fiber), and C is speed of light in vacuum. The other terms have the same definitions than in the equation previously published:[4] α is the absorption in the crystal, x is the thickness of the crystal, $\phi(t)$ is the ultrasonic modulation, and $\gamma = \gamma' + ig''$ is the photorefractive amplitude gain. In this expression, the first term between the braces represents the diffracted reference beam and the second term is the transmitted signal beam.

From equation (1), the intensity at the detector, I_d, can be easily calculated. Assuming that the spectrum analyzer only records the amplitude of the oscillating terms and putting the amplitude of the ultrasonic modulation ($\phi(t)$) to 0, the expression for the signal intensity at the detector becomes:

$$I_d(x,t) = I_d(0,0)4Ae^{(\gamma'-\alpha)x}\sin(\delta/2)\sin(\gamma'' x) \quad (3)$$

The only terms varying as function phase noise frequency in equation (3) is $\sin(\delta/2)$. The absolute value of this expression was convolved with the experimental frequency response of the detectors and plotted along with the experimental results with L and n as adjustable parameters to match the case of a 15 m path length difference. The best match was obtained for L = 14 m. and n = 1.5, in good agreement with the experimental conditions. The corresponding normalized curve is also plotted in Figure 5.

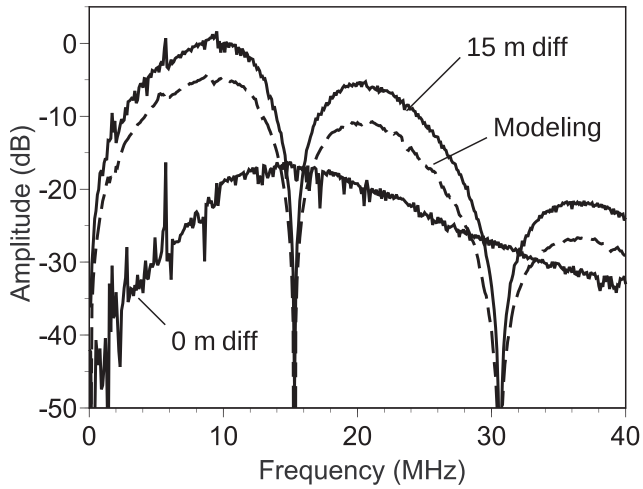


Figure 5 Normalized spectra produced by the two-wave mixing photorefractive interferometer with the phase modulator in the noise position with 0 m and 15 m path difference between the beams. Normalized modeling results are also plotted. The modeling curve was offseted by -5 dB for clarity sake.

Figure 5 shows a significant difference between the two experimental cases. The curve corresponding to 0 m difference in the path lengths of the reference and signal beams follows closely the frequency response of the detectors. The curve corresponding to the 15 m difference in path length, however, exhibits regular oscillations of large amplitude, reaching more than 20 dB above the 0 m diff curve and then dropping below –50 dB at ~15 MHz and ~30 MHz. These oscillations are very well reproduced by the modeling curve for the values of n = 1.5 and L = 14 m. A refractive index value of 1.5 is in very good agreement with the value generally used for optical fibers and a path difference of 14 m is very close of the 15 m difference in optical fibers length considering that a small part of the path was in air and was not taken into account.

The phase noise rejection capabilities of the photorefractive two-wave-mixing interferometer were also experimentally tested by measuring SNR as a function of light power. The optical part of the experimental setup was similar to the one sketched in Figure 3 with the phase modulator in signal position. The NPRO was a Lightwave® model 126 NPRO and a mechanical shutter was installed before the injection into the signal fiber. Signal durations needed to be limited to 1 ms by a mechanical shutter running at 10 Hz because the standard detection electronics of the TWM was replaced by a larger-dynamic-range electronic module especially designed for the LaserUT systems. This electronic module was not compatible with continuous-wave operations. The optical path lengths of the reference and signal beams were matched within a precision of a few cm.

A 3-MHz 8-mV source, corresponding to a 0.12 milliradian modulation, drove the phase modulator. The spectrum analyzer not being compatible with pulsed operations, signals were recorded by a digital oscilloscope and transferred to a computer. The signal was then Fourier transformed into the frequency domain. Frequency spectra were averaged 100 times for each measurement point.

SNR was evaluated from the spectra by dividing the maximum value in the 2.9-3.1 MHz band by the average of the amplitude values in the 0.5-2.9 and 3.1-5.0 MHz bands. The error in SNR measurements was estimated by repetitively evaluating the SNR for fixed light powers. The estimated error is approximately 3%. Light power was varied using a variable neutral density attenuator at the entrance of the signal fiber. SNR values were evaluated for light power values between 0 and 25 mW. Light power was the average of the sum of the DC components of both photodetectors, corrected for electronic gain and efficiency of the photodetectors. The resulting SNR vs. light power is presented in Figure 6.

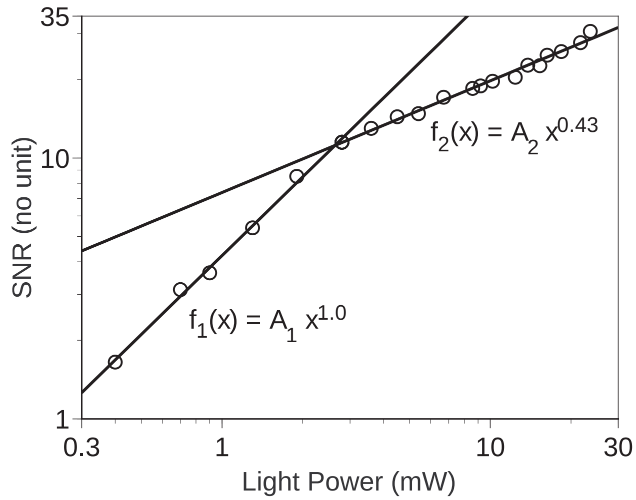


Figure 6 SNR as a function collected light power for a two-wave mixing photorefractive interferometer.

The points in Figure 6 presents two trends that are highlighted by non-linear least square curve fits. For light powers below 3 mW, the SNR appears to increase linearly whereas above 3 mW, SNR increases almost as the square root of the light power. The square-root relationship between SNR and light power indicates that noise is dominated by photon statistics (shot noise). This situation is the best possible experimental situation. For light powers below 3 mW, the linear relationship indicates that a source of noise other than photon statistics dominates noise. The linear relationship suggests that the principal noise source is electronics but further analysis would be required to confirm this assumption.

Conclusions: The capability of a two-wave-mixing photorefractive interferometer to reject laser phase noise using almost identical path lengths for the reference and signal beams was demonstrated experimentally. It was shown that a linear cavity laser can achieve performances similar to a significantly more expensive non-planar-ring oscillator laser of the same power with the appropriate matching of the reference and signal path lengths.

Also, it was demonstrated that the two-wave-mixing photorefractive interferometer can perform shot-noise limited measurements at light levels higher than what is possible with a conventional dual-cavity Fabry-Perot interferometer. Combined with its ability to reject amplitude noise, the photorefractive interferometer can be used to achieve very sensitive measurements with the appropriate levels of collected light. In this paper, it was also demonstrated that the speckle effect caused by composite surface roughness should not limit the use of a photorefractive interferometer for composite inspection. However, the proposed scheme[13] to compensate for the Doppler shift created by scanning the detection laser beam on a surface still remains to be demonstrated in actual composite inspections to consider the two-wave photorefractive interferometer as a replacement of the confocal Fabry-Perot interferometer currently used in LaserUT systems.

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