Retraction

It has come to the attention of the Institute of Physics that this article should not have been submitted for publication owing to its substantial replication of an earlier paper (Michael Peeters, Guy Verschaffelt, Hugo Thienpont, Shyam K Mandre, Ingo Fischer, Martin Grabherr 2005 Spatial Decoherence of Pulsed Broad-Area Vertical-Cavity Surface-Emitting Lasers Optics Express 13 9337. Consequently this paper has been retracted by the Institute of Physics and by the authors.
Speckle Reduction Based on Ultrashort Laser Pulse

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Abstract. In this paper, a method to reduce spatial coherence of the emission and improve intensity distribution by ultrashort laser pulses has been proposed. The spatial decoherence manifests itself in the formation of a Gaussian far field intensity distribution. For lasers with a high Fresnel number, the loss of full spatial coherence is usually due to the coemission of multiple mutually incoherent transverse modes, which are individually fully spatially coherent. That is to say, it is due to breakdown of the modal emission of these lasers.

1. Introduction
Laser with high monochromaticity, luminance and directivity has been applied in vision detection widely. But for its perfect coherence, such image system always is disturbed by speckle noise, which changes image grey tempestuously, reduces resolution and hides details of the image. So many methods have been provided to restrain speckle noise, such as homomorphic filter, Lee and wavelet threshold algorithms. On one hand, they reduce speckle noise, and on the other hand, they also make details of the image lost. So it is very important to improve precision and restrain speckle noise in the process of image forming. In this paper, an inhibiting method of using ultrashort laser pulses to reduce spatial coherence and improve intensity distribution has been provided, which is based on the principle of the relation between spectrum character and coherence of optical field. So it is not necessary to use multimode fibre or complex optical arrays with this method.

2. Factors of influencing speckle
When laser with coherence illuminates an object, because of the object’s coarse surface compared to wavelength, intensity on image is superimposed by lasers reflected from independent units of the surface. The different distance between wavelets travel is several or many wavelengths, and speckle noise is formed by interference of wavelets. Superimposing beams of laser will generate two uttermost results, one of which brings complete interference pattern by superimposing amplitude, and the other can not generate interference pattern by superimposing intensity. In fact, for the limitation of light source, partial coherent source between them has been applied widely like semiconductor laser and excimer laser.

One of the basic characters of laser is perfect directivity. But absolute coherence is not necessary condition to realize good directivity, and partial coherent light also can form the same intensity distribution as laser in far field. According to diffraction integral theory [1], intensity distribution is as follows:

$$J(r) = \rho(r) \int_{A} \mu(r)\delta(r)e^{ikr}dA$$

(1)
r is a two-dimensional vector in integral plane, and k is wave number. \( \delta(r) \) is PSK of the image system, and \( \rho(r) \) is input beam described by Gauss model. So \( \mu(r) \) is also presented by Gauss function:

\[
\mu(r) = \exp(-\frac{r^2}{2\sigma^2})
\]

(2)

\( \xi \) is RMS of source coherence degree. The coherence degree includes time and spatial coherence degree. In the next part of this paper, we will show both of them how to affect speckle forming.

2.1. Time coherence degree

Time coherence of optical field is decided by longitudinal coherence length \( L_C \), and it is described as:

\[
L_C = \frac{\lambda^2}{\Delta \lambda}
\]

(3)

\( \lambda \) is the wavelength and \( \Delta \lambda \) is line breath. So time coherence depends on configuration of spectrum, and if longitudinal coherence length of wider spectrum light is shorter, coherence of source is worse.

Partial coherent light passes optical system, and speckle will be found on the image plane, special parameter of which is speckle contrast \( C^2 \):

\[
C = \sqrt{\frac{<I^2>-<I>^2}{<I>}}
\]

(4)

\( I \) is intensity of image. Speckle contrast is a parameter to evaluate weakness or strength of speckle on image, which is larger, speckle noise of the image is stronger. According to reference 3, \( C^2 \) is shown approximately as:

\[
C^2 = \int_{-\infty}^{\infty} \rho(\Delta r)d\Delta r
\]

(5)

On the assumption that the distribution of light source is Gauss pattern, time coherence function \( \rho(\Delta r) \) uses longitudinal coherence length as dependent variable.

\[
\rho(\Delta r) = \exp\left[ -\sqrt{\frac{\ln 2\Delta r}{L_C^2}} \right] \cdot \cos(2\pi \Delta r / \lambda_0)
\]

(6)

In the above equation, \( \Delta r \) stands for path length difference between two arbitrary chosen scattered waves. \( I_0 \) is intensity and \( \lambda_0 \) is wavelength. \( \rho(\Delta r) \) is probability density function of path length difference. Currently, many literatures have researched transportation of photons further. In this paper, we adopt Monte Carlo to imitate \( \rho(\Delta r) \) as shown in reference 4. The optical properties of the turbid medium are assumed as follows: the scattering coefficient is 0.1mm, the absorption coefficient is 0.0mm and the anisotropy factor is 0.5. From the parameters, we can get \( \rho(\Delta r) \), take it into formula 5 and relation between speckle contrast and longitudinal coherence length is shown in Figure 1.

With longitudinal coherence length increasing, speckle contrast is enlarged. If we want to restrain speckle noise, reducing \( L_C \) is a good choice, which means to broaden the spectrum of source.

2.2. Spatial coherence degree

Spatial coherence of beam is decided by transverse modes of laser. For multimode with a very complex transverse mode structure, angle of divergence is larger, parallelism is worse and optical field of different mode is non-coherent. So multimode can be regarded as superimposing of non-coherent Gauss distribution with fundamental transverse mode. These fundamental transverse modes are independent and form partial coherent light together. This kind of multimode laser uses \( M^2 \) as quality evaluation:

\[
M^2 = \sqrt{1 + \frac{r_0^2}{D_c^2}}
\]

(7)
$r_0$ is waist radius of beam, $D_C = \lambda / \theta$, $D_C$ is transverse coherence length with $\theta$ angle of divergence. $D_C$ and $M^2$ are indexes depicting spatial coherence and quality of beam. When $D_C$ is shorter, spatial coherence of beam is worse and the value of $M^2$ is larger. According to reference 5, simulate variance of intensity fluctuation. Suppose wave length is 630nm and waist radius is 30mm, relation of $C^2$ and $D_C$ is represented in Figure 2.

From the Figure 2, when the transverse coherence length is smaller, with increasing of transverse coherence length, speckle contrast is enhancing gradually, and out of special scope, speckle contrast never changes. So if transverse coherence length is reduced in certain domain, speckle noise is relieved on the image plane.

3. Principle of restraining speckle based on ultrashort laser pulse

With the characters of high speed and powerful electric intensity, ultrashort pulse laser has been applied in so many domains like laser process. Accordingly, under the case of lower pulse energy, adopting spectrum broad band performance, ultrashort pulse laser can also develop new measurement application.

3.1. Generation of ultrashort laser pulse and suppression to speckle

Currently, we utilize two approaches of generating ultrashort laser pulse. One is finished by lock mode of solid state laser. Except that the methods of condensing pulse in laser with NOLM, using initiative lock mode dispersion to manage fibre laser to can also generate pulse. Both of methods broaden spectrum by compressing light pulse, and this laser system is composed of oscillator, stretcher, amplifier and compressor. In oscillator, ultrashort pulse is generated by special technology, then, stretcher widens pulse in time according to different wavelength, so amplifier can get enough energy, and different spectrum after amplified will be assembled together by compressor to recover short pulse duration. Under above analysis about elements influencing speckle, the pulse laser with broadened spectrum can restrain speckle noise.

Moreover, under the control of pulse electricity, laser can produce ultrashort laser pulse with fixed frequency as clock. So we choose VCSEL [6] with lower price to produce ultrashort laser pulse by control of pulse electricity, then, analyze speckle noise on image plane.

3.2. Imaging by ultrashort laser pulse based on VCSEL

VCSEL is made up of semiconductor laser and resonant cavity with vertical gain from surface radiation, which laser cavity is vertical to layer with power of semiconductor. Compared to traditional laser of radiation from edge, beam is sent out from vertical direction of foundation. Resonant cavity of VCSEL is smaller than traditional laser, which is easy to engender micro-cavity effect and form electricity excitation of very low threshold.
3.2.1. Analysis of elements influencing VCSEL. Due to the extremely short cavity length of the order of one wavelength, these lasers inherently emit in a single longitudinal mode. For a small enough aperture diameter of a few µm, the VCSEL cavity will only support the fundamental transverse mode. To increase the available output power, large aperture is used which easily becomes multimode with a very complex transverse mode structure. Some studies have shown that a VCSEL under CW operation can show complex pattern [7]. In this paper, we show that when a VCSEL with large oxide aperture is driven by a strong current pulse, the modal description of the emission breaks down. By tuning the pulse duration and amplitude, we can significantly change the spatial coherence of VCSEL. Results show it is a simple way to generate partially coherent. Sources with a reduced degree of spatial coherence may find many applications. They have been proposed as a way to increase the image quality and the depth of focus in imaging systems.

A way of FD-BPM [8] is adopted in this paper to simulate oxide VCSEL model, results are shown in Figure 3 and Figure 4. The first indicates intensity of relative electric field $E_r$ along the radius of oxide aperture changed differently under different oxide apertures (4µm and 8µm), when input electricity is 0.67mA. Optical field gives priority to fundamental mode when oxide aperture is less than 6µm, and with the size of oxide aperture increasing, intensity is not always enhancing. Higher modes will appear after radius of oxide aperture is larger than 6µm, fundamental transverse mode insures high quality of laser, but with increasing of produced electricity, higher modes begin to vibrate as shown in Figure 4. Suppose $I_{th}$ is electricity of threshold, $E_r$ follows Gauss distribution near $2I_{th}$, but second-order transverse mode appears at $5I_{th}$, the generation of higher modes are influenced by two factors, larger oxide aperture and injection electricity, and it means the factors can change coherence length. Based on the analysis, only need to use VCSEL to restrain speckle noise with larger oxide aperture and changeable injection electricity.

In addition, the wavelength shift $\Delta \lambda$ was measured as a function of the pulse duration $T$. It could be well fitted by a power law $\Delta \lambda(T) = Q(T/r)^b$ with a timescale $r$ of 1.56µs, an exponent $b$ of 0.13 and a factor $Q$ of 2.38nm, as research before by M.Grabherr [9]. Accordingly, the pulse durations directly affect spectrum scope. So we can significantly reduce the spatial coherence of input laser to restrain speckle contrast.

3.2.2. Results of experiments. Some experiments are done to analyze speckle noise on coarse surface illuminated by large oxide aperture VCSEL under control of pulse electricity with different durations and intensity, and relation curve is given in Figure 5 and Figure 6. Starting with high pulse amplitude and for small pulse durations, the contrast of speckles is maximal. Then increasing the pulse duration and fixing pulse amplitude, the contrast monotonically drops. Until a pulse duration of a few µs, the contrast decreases severely during tens of µs. After this, the contrast increases again to the starting value. On the contrary, increase of the pulse amplitude results in a monotonous decrease of the contrast of the speckles at fixed pulse duration. So control these factors rationally in laser illumination applications, we can get distinct details of images with less speckle noise.
4. Conclusion
In this paper, a method of restraining speckle based on ultrashort pulse laser was brought forward under the analysis of factors which influence coherence of laser. It makes higher modes of VCSEL vibrate through adjusting duration and intensity of pulse electricity and reduces coherence of beams. So it is not necessary to use multimode fiber or complex optical array to decrease speckle noise and only needs to change the emission to homogeneous laser by varying the pulse parameters.

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