Ultrafast web inspection with hybrid dispersion laser scanner

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We report an ultrafast web inspector that operates at a 1000 times higher scan rate than conventional methods. This system is based on a hybrid dispersion laser scanner that performs line scans at nearly 100 MHz. Specifically, we demonstrate web inspection with detectable resolution of 48.6 μm/pixel (scan direction) × 23 μm (web flow direction) within a width of view of 6 mm at a record high scan rate of 90.9 MHz. We demonstrate the identification and evaluation of particles on silicon wafers. This method holds great promise for speeding up quality control and hence reducing manufacturing costs.

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1. Introduction

Web inspection (also called surface inspection) is a widely used machine vision application for nondestructive evaluation of products during manufacturing [1,2]. Its applications include quality control, defect detection, and dimensional metrology in screening of fabrics, paper, liquid crystal display panels, thin films, and silicon wafers [1–4]. As devices to be inspected are getting thinner (e.g., organic LED display panels), roll-to-roll inspection methods are becoming the standardized model for web inspection. The ability to scan the surface of such materials or devices at high speed is particularly important for inspecting a large quantity or surface area in a short period of time, leading to reduction of manufacturing costs and improvement in the precision of quality control [1–4].

Conventional methods for web inspection are mainly categorized into two types: (1) a line scan camera with a white light source [1,2,5–8] and (2) a laser scanner with a single-pixel photodetector [9,10]. In the first type, white light is incident onto a

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web that flows in a continuous reel, and scattered light from unwanted objects (e.g., dust particles or defects) on the web is detected by an array detector or the so-called line scan camera (typically, a single-array CMOS camera). Here the scan speed (hence, the web's flow speed) is limited by the frame rate of the CMOS camera (typically up to 100 kHz corresponding to a web flow speed of ~10 cm/s), provided that a sufficient intensity of light illuminates the web for sensitive detection. In the second type, continuous-wave laser light is linearly scanned over the web in the orthogonal direction to the web's flow repeatedly, and the resultant scattered light from dust particles or defects is detected by a sensitive single-pixel photodetector. While the detector's response is fast due to its single-pixel readout, the scan speed is limited by the scan rate of the laser scanner (typically up to 10 kHz due to the inertia of the mechanical scanner, corresponding to a web flow speed of ~1 cm/s). In many applications, the first method is preferred for operation due to its higher scan speed. Yet, there is a strong market demand for higher speed in web inspection and hence further cost reduction in manufacturing.

In this paper, we propose and demonstrate a method for web inspection that operates at a few orders of magnitude higher scan rates than conventional web inspectors. Our method is based on the use of the ultrafast laser scanner that has recently been developed by us, known as the hybrid dispersion laser scanner (HDLS) [11]—an optical method that uses a combination of spatially and temporally dispersive elements with a broadband mode-locked laser to achieve ultrafast laser scanning at the scan rate equivalent to the laser's pulse repetition rate (typically on the order of 10 MHz). Consequently, our web inspection system that we refer to as the HDLS inspector performs nondestructive evaluation of a continuously running web at a record high scan rate of 90.9 MHz, nearly 1000 times faster than currently employed technologies. The resultant images obtained from the HDLS inspector can be used to classify dust particles or defects in the digital domain. This method holds great promise for speeding up quality control and hence providing higher cost performance in manufacturing.

2. Experimental Apparatus

The HDLS inspector is schematically shown in Fig. 1. The optical source is a mode-locked Ti:sapphire laser that emits a train of broadband pulses with an optical bandwidth of 10 nm centered at 800 nm at a pulse repetition rate of 90.9 MHz. Each pulse enters a dispersive fiber with a group-velocity dispersion of −650 ps/nm that temporally stretches the pulse with shorter/longer wavelengths traveling faster/slower—a process known as dispersive Fourier transformation [12]. Then, the stretched pulse is incident onto a pair of diffraction gratings with an equal groove density of 2200 lines/mm that maps the spectrum of the pulse along a 1D spatial line. The 1D rainbow then enters a pair of cylindrical lenses (i.e., a cylindrical beam expander) to produce a wider rainbow, which is focused onto the target web via a cylindrical

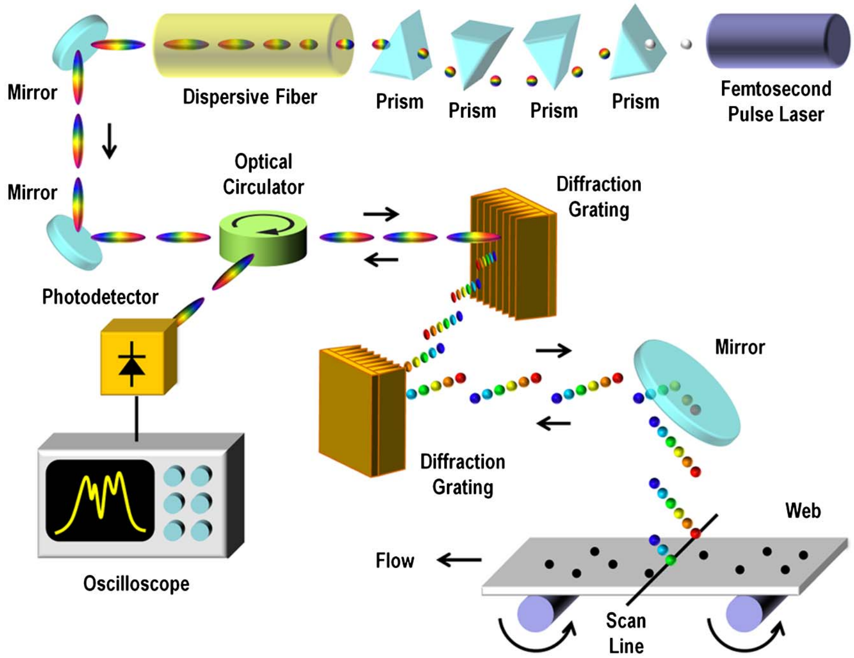

Fig. 1. Schematic of the HDLS inspector. The spectrum of each pulse from the laser is temporally stretched by the dispersive fiber and is then spatially dispersed by the pair of diffraction gratings and incident onto the target web. Different frequency components of the pulse arrive at different spatial coordinates on the web at different times successively, resulting in a laser scan. Here, the web is reflective while dust particles on it scatter the incident light. The reflection from the web is detected and digitized by the photodetector and oscilloscope, respectively. The colors of the pulses in the figure are only for illustrative purposes and do not represent the real wavelengths.

lens with a focal length of 38 mm. Consequently, the size of the rainbow on the web is estimated to be 6 mm × 40 μm, with the long and short axes orthogonal to and in parallel with the web flow's direction, respectively. While the HDLS inspector works in both reflection and transmission modes (when the target is reflective or transmissive), the reflection mode is employed in our proof-of-principle demonstration. The target web is a polished silicon wafer with dust particles on top of a motor-controlled translation stage. The reflected light from the target web is collected by the same lens system, but is directed via an optical circulator toward a high-speed photodetector with a detection bandwidth of 12.5 GHz. Finally, the pulse measured by the photodetector is digitized in real time by a high-speed oscilloscope with a bandwidth and a sampling rate of 7 GHz and 20 GS/s, respectively, and is then subject to digital signal processing for image construction.

3. Results

The basic performance of the HDLS inspector is shown in Fig. 2. The figure shows the signal with and without dust particles on the fixed web measured by the photodetector and displayed on the oscilloscope. Each pulse corresponds to a single inertia-free lateral scan. As shown in the figure, the period of the measured pulses is 11 ns, corresponding to the pulse repetition rate of the laser (90.9 MHz). Here the target web is reflective while dust particles scatter the incident light, hindering the light from returning to the collection optics. Consequently, in the presence of a dust particle, its signature is imprinted as a small dip on the measured background signal as shown in the inset of Fig. 2. With the translation stage, consecutive 1D scans can be combined to construct a

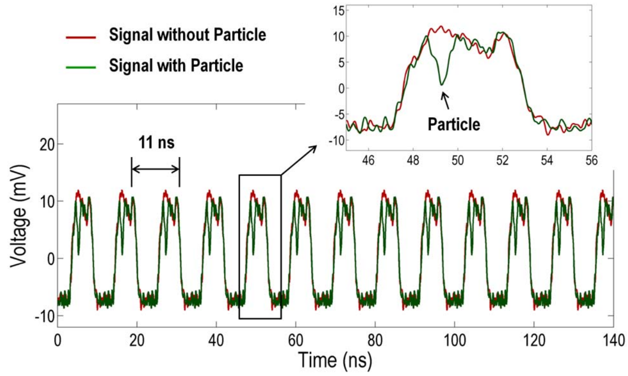

Fig. 2. Train of pulses with and without a dust particle captured by the photodetector and displayed on the oscilloscope. The pulse interval is 11 ns, corresponding to the scan rate of 90.9 MHz. The figure inset shows a dip in the signal that corresponds to the presence of a particle.

2D image of the web, from which the morphological properties (i.e., size and shape) of the particle can be obtained.

We determined the spatial resolution of the HDLS inspector in both the scan and web flow directions using two different methods. In the scan direction, we found the resolution to be 388 μm by evaluating the intensity of the reflection of an incident Gaussian beam from a translating USAF-1951 resolution test target that consists of transparent and opaque regions [Figs. 3(a) and 3(b)]. Here it is important to note that while the resolution is relatively large, it does not limit the inspector's ability to detect smaller particles than the resolution. In fact, we estimated the inspector's sensitivity or detectable resolution to be 48.6 μm/pixel (based on our digitizer's sampling rate of 20 GS/s) by tracking the position of

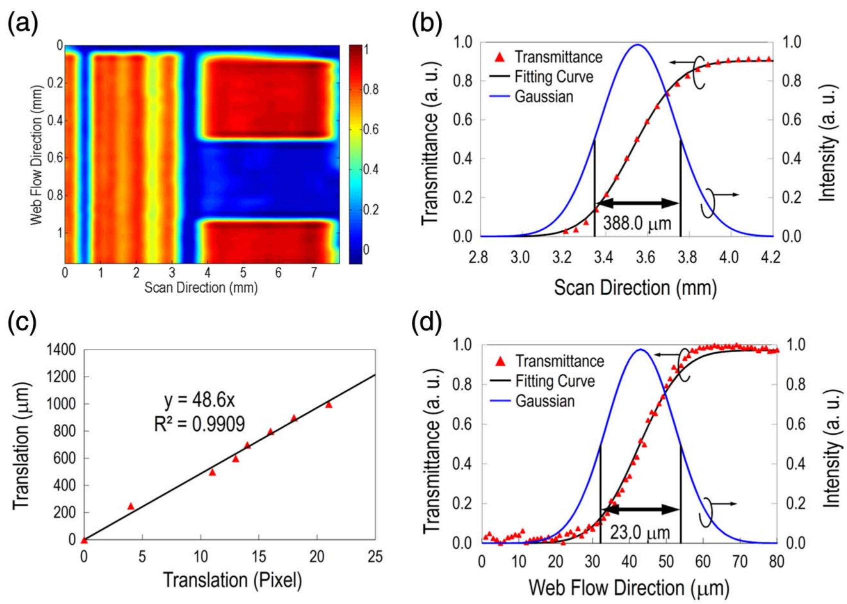

Fig. 3. Resolution and detectability of the HDLS inspector. (a) USAF-1951 resolution test target imaged by the HDLS inspector. (b) Determination of the resolution in the scan direction. (c) Determination of the detectability in the scan direction. (d) Determination of the resolution in the web flow direction.

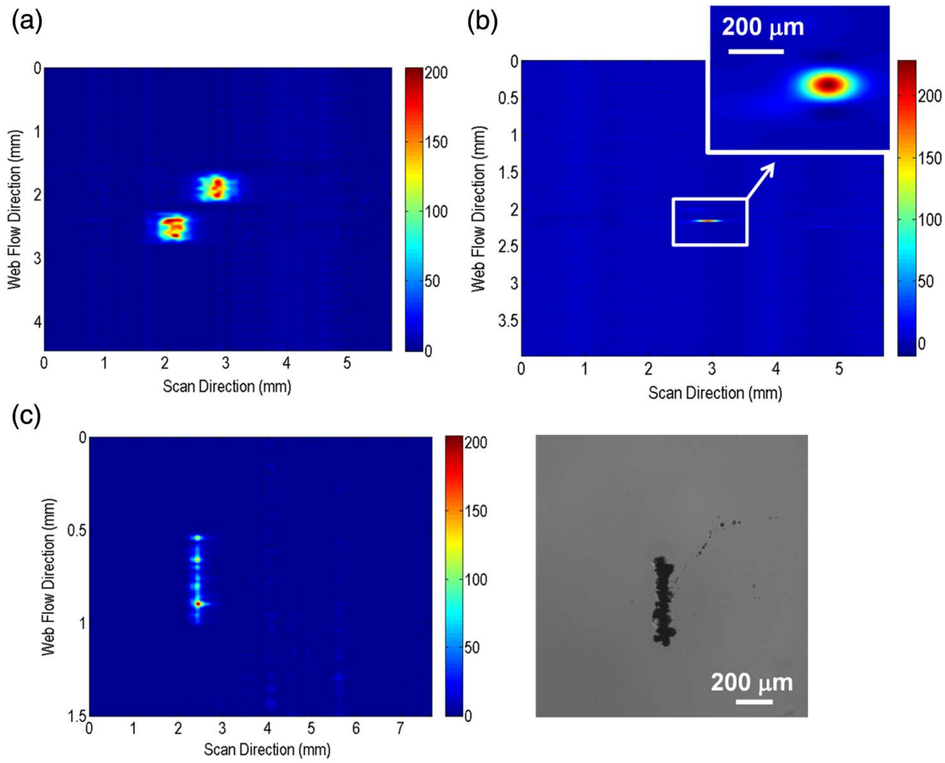

Fig. 4. Identification of dust particles with the HDLS inspector. (a) Pair of medium-sized dust particles of identical dimensions (400 μm × 300 μm) captured by the HDLS inspector. (b) Small dust particle (40 μm × 70 μm) captured by the HDLS inspector. The inset shows a magnified image of the particle. (c) Scratch (i.e., defect) on the silicon wafer captured by the HDLS inspector in comparison with a microscope image of the scratch.

the reflected Gaussian beam's peak intensity when translating the sample [Fig. 3(c)]. The inspector's detectability is expected to improve as the sampling rate of the digitizer is increased. In the web flow direction, we found the resolution to be 23.0 μm by using a knife-edge technique and fitting the intensity of the reflection with a Gaussian function [Fig. 3(d)]. Here the resolution is roughly equivalent to the waist of the incident Gaussian beam in the web flow direction. Overall, the particle detectability of the HDLS inspector is 48.6 μm/pixel (scan direction) × 23.0 μm (web flow direction). The highest possible speed of the web can be found from the resolution in the web flow direction (23 μm) multiplied by the scan rate (90.9 MHz) to be 2.1 km/s or 125 km/min, which is roughly three orders of magnitude faster than the web flow speed of conventional web inspectors.

To demonstrate the HDLS inspector's ability to detect small particles, we used it to perform real-time identification of dust particles on flowing webs (Fig. 4). Since we could not produce such a high-speed flow speed as 125 km/min, we motor-controlled the web's flow in a stepping mode with each step size of 40 μm. Figures 4(a)–4(c) show the inspector's identification of dust particles whose sizes range from 40 to 400 μm within the wafer width of 6 mm. Figure 4(a) shows the presence of two 400 μm particles with nearly 500 μm spacing on the wafer. Figure 4(b) shows the presence of a single 40 μm particle whose details are shown in the figure inset. From these images, the dust particles can be classified in terms of morphological properties (i.e., size and shape) for further evaluation in the digital domain. Finally, Fig. 4(c) shows the identification of a scratch (i.e., defect) on a silicon wafer in comparison with a microscope image of the scratch.

4. Conclusions

We have proposed and demonstrated an ultrafast web inspection system based on the HDLS—a method that performs ultrafast laser scanning with spatiotemporal dispersion. This ultrafast web inspector has a detectable resolution of 48.6 μm/pixel in the scan direction (based on a digitizer sampling rate of 20 GS/s) and 23 μm in the web flow direction within a web width of 6 mm at a scan rate of 90.9 MHz (corresponding to the highest possible web speed of 2.1 km/s)—roughly three orders of magnitude higher than the scan rate of conventional web inspectors. As a proof-of-principle demonstration, we have used the inspector to perform real-time web inspection of silicon wafers with dust particles ranging in size from 40 to 400 μm. Our method holds promise for reducing manufacturing costs and hence responding to the market needs.

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