IOP Publishing Journal of Optics
J. Opt. 19 (2017) 060402 (5pp) https://doi.org/10.1088/2040-8986/aa7251

Editorial

Perspective on speckle spectrometers

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1. Introduction

A speckle pattern denotes a random granular distribution of intensity generated, e.g., by light scattered from a rough surface or transmitted through a multimode fiber. Since speckle usually corrupts an optical image or scrambles the information sent through a fiber, there have been considerable efforts to suppress the formation of speckle. However, the speckle is useful in many ways, e.g., its sensitivity to a change of the structure that produces it has been widely used for metrology and sensing applications. When the structure is fixed, the speckle pattern can be used to extract information of the illuminating light. One example is a speckle spectrometer, which retrieves the spectrum of light from the speckle pattern it creates.

The most common spectrometers use a grating to diffract light of different frequency to different angle. Two adjacent frequencies, which have slightly different diffraction angles, can only be spatially separated and measured by different detectors after propagating over a long distance. The spectral resolution scales with the distance from the grating to the detector; the smaller the spectrometer, the lower the resolution. The tradeoff between resolution and size seriously limits the performance of chip-scale spectrometers—a key element for low-cost, portable sensing and lab-on-a-chip applications, hence prompting intense exploration of alternative mechanisms for spectrometer operation.

The one-to-one spectral to spatial mapping (one frequency mapped to one spatial position) is not necessary for spectrum measurement. As long as each frequency corresponds to a distinct spatial distribution of intensity across the detector array, the spectrum can still be recovered. The multiplex spatial-to-spectral mapping relaxes the requirement for dispersive medium, and diversifies the spectrometer design.

2. On-chip random spectrometer

Light scattering by a disordered structure generates frequency-dependent speckle pattern, which can be used as a spectral fingerprint to identify the spectrum [1]. The spectral-to-spatial mapping is calibrated with a tunable light source and recorded in a transfer matrix, whose columns represent the intensity distributions over all detectors at individual frequencies. An unknown spectrum, which is a combination of these frequencies, is then reconstructed from the measured speckle pattern via matrix inversion or nonlinear optimization.

The spectral resolution is determined by how fast the speckle pattern decorrelates with frequency. It can be estimated from the width of the spectral correlation function, which reflects a minimal frequency shift to produce a noticeable change of speckle pattern [1]. Single scattering from a thin disordered material or diffraction from a random polychromat gives a linear scaling of the spectral resolution with the distance to the camera that records the far-field speckle pattern [2–5]. Multiple scattering in a thick random medium accelerates the speckle decorrelation by increasing interaction length and enhancing spectral-spatial diversity [1]. For a lossless diffusive medium, the spectral resolution scales quadratically with the medium size L, thus it increases more rapidly with L than the case of single scattering/diffraction.

While multiple scattering enhances spectral resolution, it reduces light transmission through the random medium (most light being reflected). The tradeoff between resolution and sensitivity was overcome in an on-chip spectrometer design [1]. The two-dimensional scattering structure is surrounded by a high-reflecting layer so that the diffusive light is effectively channeled through the disordered medium to the detectors. Sub-nanometer resolution at wavelength $\lambda = 1500\,\mathrm{nm}$ was achieved with a disordered photonic chip of lateral dimension less than $100\,\mu\mathrm{m}$.

The number of independent spectral channels that can be retrieved from a single speckle pattern is limited by the number of speckle grains [1]. The operation bandwidth (continuous frequency range covered by a single acquisition) is given by the product of the number of (measured) speckle grains and the spectral width of each spectral channel (approximately the spectral correlation width). Unlike a grating spectrometer, there is no requirement that the spectral channels of a random spectrometer be contiguous. If the probe signals are confined to separated spectral regions, the transfer matrix only needs to cover those regions, providing a more efficient use of the spectral channels.

One significant advantage of the random spectrometer over conventional spectrometers is that it does not suffer the redundancy set by the free spectral range, as a random structure breaks any symmetry or degeneracy. Each speckle is formed by interference of a vast number of waves with randomized phases, so the probability of having identical speckle patterns for two distinct frequencies is negligibly small.

Another advantage of the random spectrometer is that it can operate over an extremely broad frequency range without structural modification. This is in sharp contrast to the grating spectrometer, which requires a rotation of the grating to diffract light of varying frequency to the detector. An on-chip grating spectrometer works only for a fixed spectral range, because the monolithic grating cannot be rotated. In a random spectrometer, the scattered light always reaches the detector array, regardless of its frequency. A switch of operation frequency is done simply by changing the transfer matrix to the one calibrated for the target spectral range.

The random spectrometer is ideally suited for compressive spectroscopy. Previous schemes rely on pseudorandom masks for single-pixel detection [6, 7], but the computation efficiency was low as different masks were used sequentially, and the amplitude modulation of masks also introduced loss. The random spectrometer overcomes these issues by performing 'random' projection of an input spectrum to multiple detectors *simultaneously*. The parallelizing operation greatly shortens acquisition time and improves signal collection efficiency.

3. Multimode fiber spectrometer

A multimode fiber (MMF) can also generate speckle via interference of the guided modes. The output speckle pattern is unique for each frequency, thus can be used to identify the spectral component of input light. In the past, the speckle contrast was used as a measure of laser linewidth [8], a recent breakthrough is the retrieval of entire spectrum from a speckle pattern [9]. A general purpose spectrometer, comprised of a single MMF and a monochrome camera (to record speckle pattern), was developed recently [10].

The spectral resolution scales linearly with the fiber length, if mode coupling in the MMF is weak. Since optical fiber has been optimized for long-distance transmission with minimal loss, a long MMF can be used to reach ultrahigh resolution without sacrificing sensitivity. A record resolution of 1 pm at $\lambda = 1500$ nm has been achieved with a 100 m long step-index MMF [11]. The resolving power exceeds 10^6, outperforming the largest bench-top grating spectrometers. Moreover, the MMF can be coiled to a small volume, making the spectrometer compact and lightweight.

Thanks to the mapping from the one-dimensional spectrum to two-dimensional (real) space, a large number of spectral channels can be measured in a single acquisition. Broad-band operation was demonstrated with a 4 cm long MMF, covering the wavelength range of 400–750 nm with 1 nm resolution [11]. The number of spectral channels that can be recovered from one speckle pattern is limited by the total number of guided modes in the fiber. While a larger core MMF supports more spatial modes, the spectral contrast would be lower for a dense spectrum; once the contrast falls below noise level, an accurate spectrum recovery is impossible.

To increase the spectrometer bandwidth, a wavelength division multiplexer (WDM) was integrated with a bundle of MMFs [12]. The WDM divides a broad spectrum to multiple subbands, each measured by one MMF. The output speckle patterns from all the MMFs are recorded simultaneously by a large-area camera (with many pixels), then they are processed separately and in parallel, greatly reducing the complexity and enhancing the speed of spectrum reconstruction. A single-shot measurement of dense spectra at $\lambda \sim 1500$ nm with 100 nm range and 0.03 nm resolution was realized with five 2 m long MMFs.

The MMF spectrometer, combined with an optical frequency comb source, is applied to broadband metrology-grade spectroscopy with comb-tooth level resolution [13]. A total of 500 comb lines were probed simultaneously and 3500 lines sequentially for direct comb spectroscopy. The frequency resolution represents a $\sim$10-fold improvement over the state-of-the-art VIPA-based and free-running dual-comb spectroscopy.

4. Spiral waveguide spectrometer

As an on-chip implementation of the MMF spectrometer, a silicon multimode waveguide was fabricated and coiled in a spiral geometry to have a long length in a small footprint [14]. The spectral resolution is strongly enhanced by introducing evanescent coupling between adjacent waveguide arms to increase temporal spread of propagating light. Such enhancement is non-resonant, broad-band, as that by multiple scattering in a diffusive medium. The spectral resolving power exceeds 10^5 in a 250 μm radius spiral structure.

Like the MMF, the spiral waveguide can effectively disperse light at any frequency where the wafer has negligible absorption and the waveguide remains multimode. Moreover, it is possible to recover many frequency components with a small number of detectors, if the spectrum is sparse in some domains [15]. Compressive sensing algorithms were adopted for rapid, accurate and robust reconstruction of various types of sparse spectra, and the operation bandwidth was increased more than eight times [14].

5. Open problems and challenges

While the speckle spectrometer already reached a record-high resolution, a further increase of resolution is straightforward, such as to increase the MMF length. However, the speckle is sensitive to environmental changes including mechanical vibration and temperature drift. Recent works showed that a combination of thermal and mechanical stabilization with software correction could enable robust performance of a speckle spectrometer [11, 13]. Alternatively, multiple transfer matrices might be calibrated at varying temperatures, and the appropriate transfer matrix could then be selected to match the current temperature.

A main constraint of the speckle spectrometer is that the probe signal must be delivered in a fixed spatial mode and polarization state to ensure that a given frequency always generates the same speckle pattern. This was done by coupling the probe signal to a single-mode, polarization-maintaining fiber or waveguide on-chip. However, it would limit the sensitivity of spectral measurement of optical sources that emit in many spatial modes. Therefore, the speckle spectrometers are most suitable for applications which already collect signals by single mode fibers, e.g., optical spectrum analyzer, telecommunication channel monitor, optical wavemeter, micro-photoluminescence spectroscopy, optical coherence tomography.

The detection noise is an important issue to the speckle spectrometer, because even monochromatic light spreads over all detectors, while in a grating spectrometer it hits a single detector. If the signal is weak or the detector noise is large, dividing the signal over many detectors would lower the sensitivity. For intense or narrow-band signals, however, the speckle spectrometer provides a comparable sensitivity to a grating spectrometer [16].

While three designs of speckle spectrometers are reviewed above, none of them is optimal. The sensitivity of an on-chip random spectrometer could be improved by engineering disorder (introducing structural correlations) [1]. The resolving power of a multimode fiber/waveguide spectrometer might be further enhanced by controlling group velocity dispersion [10]. The inverse structural design, which is challenging for multiple scattering of light, may provide the best performance for specific applications. An alternative scheme might be a reconfigurable spectrometer that adjusts the speckle-generating structure in real time to optimize spectral measurement.

6. Closing remarks and outlook

The dependence of a speckle pattern on the polarization state and spatial wavefront, in addition to the spectrum of light, can be utilized for multifunctional detection. The variation of speckle pattern with input polarization was used to measure the spectrally dependent polarization state of an optical field [17]. The sensitivity of the speckle pattern to the spatial location of emitters might be explored for hyperspectral imaging.

Speckle spectrometers, based on spectrum-to-space mapping, also inspired the application of reverse mapping (from space to spectrum) for spectrally encoded (spatial) imaging [18, 19]. The frequency-varying speckle patterns were used for single-detector imaging with compressed sensing acquisition [20]. To conclude, complex photonic structures that couple many degrees of freedom in different domains, together with recently developed computational algorithms, have brought and will continue bringing new concepts and breakthroughs for imaging and sensing.

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