High-speed harvesting of random numbers

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Human-made physical random number generators (RNGs) can be traced back 5000 years or more. Early examples such as knucklebones, two-sided throwsticks, or dice have been found in the Middle East, India, and China. RNGs were used for fortune telling and games of chance, with the oldest known board games of similar age as those of the number generators. Today, RNGs are vital for services and state-of-the-art technologies such as cryptographically secured communication, blockchain technologies, and quantum key distribution. Moreover, RNGs are needed in machine learning and scientific applications such as Monte Carlo numerical methods. On page 948 of this is- sue, Kim *et al*. (*1*) demonstrate an ultrafast RNG based on a broad-area laser with a multispot beam that is analogous to generating random numbers by using many dice at once.

Random numbers are often generated by using a software algorithm running on a computer, called “pseudo”-random because the sequence eventually repeats. Moreover, relations among the numbers can exist that reveal that the numbers are not uniformly random. Hence, true RNGs (TRNGs) are of great interest, providing random numbers based on physical measurements that involve some noisy or stochastic process. All TRNGs have some nonidealities, such as generating zeroes more frequently than ones for a binary-output device, which must be mitigated by carefully engineering the device and postprocessing the data to improve the randomness quality (*2*).

Some applications require generating random numbers at very high rates, such as encrypting data in cloud-computing data centers, high-speed communication net- works, or massive simulations. Photonic de- vices are a natural fit for these applications because of their potential for high-speed operation, compact size for chip-scale devices, and low power consumption.

Recently, Marangon *et al.* (*3*) developed a TRNG that is based on interfering two dif- ferent lasers on a beam splitter and detecting the resulting powers that emanate from its two output ports. The randomness comes about from quantum fluctuations in a laser due to a process known as spontaneous emission of photons. This process randomizes the phase of the light emitted by each laser, and this phase variation is converted to an intensity variation through the interference effect. Measuring which output port of the

interferometer has the higher or lower intensity can be used to generate a one or a zero, respectively, at random. A compact device can be realized by generating random numbers in real time at a rate of 8 Gb/s for days at a time, passing tests that are used to assess the quality of the bit stream.

The bottleneck in reaching higher speeds is that the lasers are single-mode and only generate a Gaussian beam–like spot at a single frequency. Kim *et al*. overcome this bottleneck by using a broad-area laser that simultaneously emits a plethora of modes, resulting in a multispot beam. The patterns undergo a complex dance, writhing and growing bright and dim because of phase and amplitude variation of the light within the laser (see the figure). For a good TRNG, engineering the broad-area laser cavity is especially necessary so that spatial and temporal correlations are minimized. The authors do so, which is a major achievement.

Common broad-area lasers are known to exhibit irregular intensity pulsations in space and time because of the nonlinear interaction of light and the laser medium (*4*). Such instabilities result in correlations of their emission with characteristic spatial and temporal scales and are exceedingly difficult to avoid. This situation has plagued attempts to apply broad-area lasers more widely. Bittner et *al*. (*5*) showed that they could largely suppress the onset of spatio-temporal instabilities by using a cavity with a D shape, inspired by chaotic billiards; the balls on a D-shaped billiard table follow chaotic trajectories (*6*).

Kim et al. introduce another approach based on adapting the shape of the cavity. After performing extensive numerical modeling, the authors chose a bow-tie shape and precisely microfabricated a laser chip. The authors managed to boost the number of modes, avoiding their locking, and thereby substantially reduced the spatial and temporal correlation scales to 1.5 μm and 2.8 ps, respectively.

Another advantage of using the spatial degree of freedom of the special laser design is avoiding the two separate lasers and interference on an auxiliary beam splitter (*3*). Random numbers can be "harvested" from the complex emitted pattern by measuring the intensity at 254 spatial positions on ultrafast time scales (on the order of 1 ps) by using a special high-speed camera. This strategy is truly an ultrafast Demeter meeting chance.

Through this effort, they achieved a random bit generation rate of 250 Tb/s, which is much more than an order of magnitude greater than previous efforts. A full technical implementation of such an ultrafast TRNG still faces several challenges that need to be overcome. The high-speed camera could only capture data over a limited time (~2 ns), so they had to collect and concatenate multiple records to generate the more than 10^9 random numbers needed for the various statistical tests of randomness. Replacing the camera with a multitude of integrated photodetectors is yet to be achieved. Also, the required postprocessing of the measured intensities to ensure randomness is, at such speed, a task for the future.

Looking beyond, the innovative approach to tailor the spatial and temporal emission properties of broad-area lasers and manipulating the nonlinear interaction of light with the laser medium opens other applications that require many degrees of freedom. Several machine-learning approaches are based on a random mapping of low-dimensional input data onto a high-dimensional- state space, which might be accomplished by injecting a data-encoded beam into a tailored laser. Hence, broad-area lasers may become attractive photonic integrated circuits for ultrafast information processing (*7*, *8*). j

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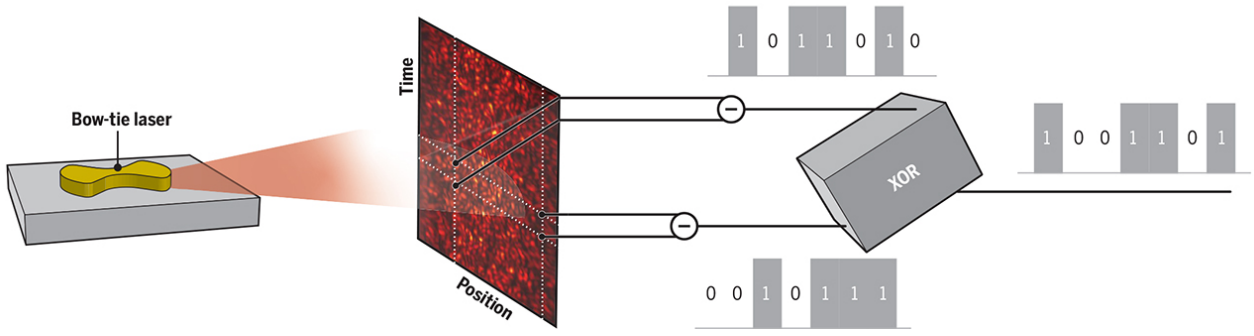
Creating bits with laser intensity

Ultrafast random bits are generated from a broad-area laser with a bow-tie cavity. In order to generate the random bits, first intensities separated by ~6 ps are subtracted from each other for the same positions on the detector. This creates bits of either ones or zeroes, which then undergo the exclusive-OR (XOR) logic operation with bits of another spot separated by half the width of the aperture. The XOR operation produces a one if the two inputs are different or a zero if the two inputs are the same. The broad-area laser allows for many different positions on the detector to be used simultaneously, allowing for fast generation of bits.



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