MICROWAVE PHOTONICS

Arbitrary waveform generation

The use of silicon photonics has now enabled the creation of 60-GHz microwave waveforms with programmable amplitude, frequency and phase.

Jianping Yao

Microwave waveforms with a large time–bandwidth product (TBWP) are extensively used in modern radar systems to improve measurement resolution and in communications systems to increase data transmission rates. Such waveforms are usually frequency-chirped (a change in the carrier frequency within the waveform) or phase-coded using digital electronics. The use of electronics, however, sets limitations on the carrier frequencies and TBWPs that can be ultimately achieved. Today, waveforms with a central frequency of up to tens or even hundreds of gigahertz are often required[1].

Writing in *Nature Photonics*[2], Maroof Khan and co-workers from Purdue University in the USA propose an optical method that can generate customized microwave waveforms with a central frequency of up to 60 GHz. Such a high frequency is attractive because it could provide very large bandwidths for communication applications such as wireless local-area networks, portable multimedia and vehicular networks.

Photonics has become a promising solution for generating high-frequency microwave waveforms. For example, photonic generation of frequency-chirped and phase-coded microwave waveforms has already been demonstrated using direct space-to-time pulse shaping[3,4], and spectral pulse shaping has been achieved using a spatial light modulator followed by frequency-to-time mapping in a dispersive medium[5,6]. However, the drawback of these techniques is that they have been implemented using expensive and complex bulk optical devices in free space, which involves complicated alignment and high coupling losses.

On the other hand, a large TBWP microwave waveform can also be generated using just fibre-optics, offering several benefits such as a much smaller size, lower loss, better stability and higher potential for integration. For example, a linearly chirped microwave waveform can be generated by spectral shaping using an optical filter with a chirped spectral response followed by wavelength-to-time mapping in a dispersive device[7]. The problem is that once fabricated, a conventional spectrum-shaping filter cannot be reconfigured, and the system therefore lacks the programmability needed for arbitrary waveform generation.

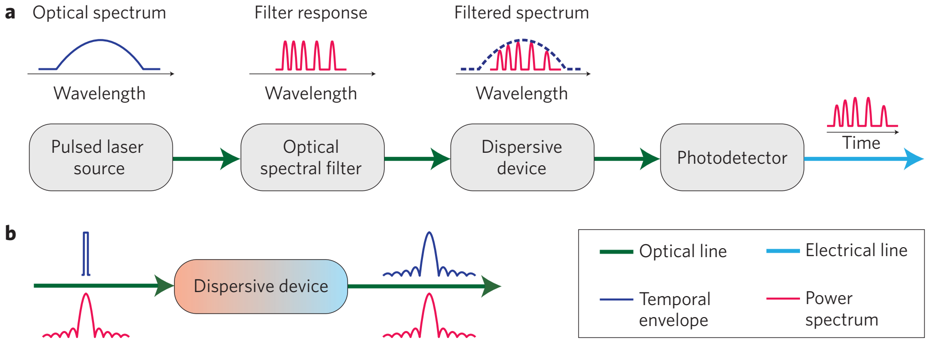

Figure 1 | Arbitrary microwave waveform generation based on optical spectral shaping and wavelength-to-time mapping. **a**, Schematic of the system. **b**, Wavelength-to-time mapping in a dispersive device.

The solution proposed by Khan and co-workers is to construct an integrated ultrabroadband arbitrary microwave waveform generator that incorporates a fully programmable spectral shaper fabricated on a silicon photonic chip[2]. The spectral shaper consists of a cascade of multichannel microring resonators on a silicon photonics platform compatible with electronic integrated circuit technology. The system reconfigurability is achieved by thermally tuning both the resonant frequencies and the coupling strengths of the microring resonators. Using such a spectral shaper, the generation of arbitrary microwave waveforms with programmable time-dependent amplitude, frequency, and phase profiles, with a central frequency of up to 60 GHz, is demonstrated.

The fundamental principle of the technique implemented by Khan *et al.* is shown in Fig. 1a, where the spectral shaper is used to modify the spectrum (spanning 1,525–1,610 nm) emitted from a mode-locked laser. The shaped spectrum then undergoes wavelength-to-time mapping in a dispersive device — a length of optical fibre — before being output as a microwave waveform in the electrical domain via a high-speed photodetector.

The wavelength-to-time mapping is valid if the duration of the input ultrashort pulse, Δt_0, and the first-order dispersion of the dispersive device, $\ddot{\Phi}$, satisfy the relation

$$\left|\frac{\Delta t_0^{\,2}}{2\ddot{\Phi}}\right| << 1$$

The output signal envelope is proportional to the Fourier transform of the input signal envelope given by[8]

$$y(t) \propto X(\omega)\,\big|_{\omega=t/\ddot{\Phi}}$$

where $y(t)$ is the complex envelope of the output optical waveform, and $X(\omega)$ is the Fourier transform of the envelope of the input optical pulse. If the input to the dispersive device is a rectangular pulse, then the output temporal waveform should be a sinc function (Fig. 1b).

The key device in the arbitrary microwave waveform generator is the spectral shaper, which needs to be reconfigurable at high speed. Khan *et al.* have developed two generations of their microring spectral shaper. In their first-generation system, the resonators have a ring structure with the central wavelength of each resonator independently tuned by a microheater placed above the microring, and have a tuning speed in the millisecond to microsecond range. Because the heating of the ring has little impact on the coupling efficiency, which is crucial in controlling the amplitude profile of the spectral shaper, Khan *et al.* produce their second-generation system by adding a coupler with a Mach–Zehnder structure in the input port of each microring. By thermally tuning the phase shift between the two arms, the coupling coefficient into the ring can be adjusted. It was demonstrated that for each resonant frequency, full tuning from the on state (no dip) to the off state can be achieved.

By incorporating the spectral shaper into a photonic arbitrary microwave waveform generation system, a variety of different waveforms are generated, including those with an apodized amplitude profile, multiple π phase shifts, two-tone waveforms and frequency-chirped waveforms[7].

It should be noted that it is beyond the capability of currently available digital electronics to generate such waveforms with a central frequency as high as 60 GHz, or to create the abrupt frequency change present in the two-tone waveform.

The major contribution of the work of Khan *et al.* is the reconfigurability offered by the integrated spectral shaper simply by thermal tuning at millisecond to microsecond speeds. Currently, the entire system is lossy and not integrated on a silicon photonic chip — a 5.5 km length of single-mode optical fibre is used as the dispersive device. If this fibre can be replaced by a highly chirped waveguide grating that can be fabricated on the same silicon photonics platform as the spectral shaper, then the system size can be greatly reduced and fully integrated. Although erbium-doped fibre amplifiers can be used to compensate the total loss of the system, including the coupling loss and the loss of the long single-mode fibre, which is about 25 dB, they increase the size of the system. One possible solution is to dope the silicon waveguides with erbium to generate optical gain without significantly increasing the size of system. ❐

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VIEW FROM... ACP 2009

A question of cost

The adoption of sophisticated phase-shift modulation schemes could make optical communication at 100 Gbit s^{-1} a reality within the next couple of years, but this is ultimately dependent on the deployment costs involved.

Rachel Won

As the demand for high-bandwidth optical communication continues to grow, there is a pressing need to find a transmission technology that can provide the necessary scalability at a competitive price. The common view of experts at the Asia Communications and Photonics (ACP) Conference and Exhibition, held from 2–6 November 2009 in Shanghai, China, was that 100 Gbit s^{-1} (100G) transmission technology based on phase-shift keying could be the answer.

Current networks operate at 1 Gbit s^{-1}, 10 Gbit s^{-1} and 40 Gbit s^{-1} (commonly referred to as 1G, 10G and 40G networks, respectively), so a move towards 100G networks should be next on the agenda. Giving an invited talk at ACP 2009 on the key technologies for next-generation transport networks, Tiejun Xia from Verizon Communications pointed out that one of the key motivations for moving from 40G to 100G networks is to provide a cost-competitive transmission technology that can support customer bandwidth demands without the need for a complete network overbuild. The cost per transmitted bit must decline at the same rate or faster than service providers can charge the customers, he emphasized.

“The main desire of service providers is to reduce the cost per bit of optical transmission by increasing spectral efficiency or the number of bits per second that can be transmitted through a given frequency band of their existing optical networking systems,” explained Jin Hong from Opnext, who was also at ACP giving an invited talk on next-generation network technology. According to Hong, service providers attempt to reduce cost primarily by increasing the channel transmission speed while maintaining the same channel spacing. The alternative of activating additional fibres is not attractive as it increases the cost per bit transmitted. “Service providers must procure fibres as well as purchase, install and maintain new optical amplifiers, filters and regenerators along the fibre route, which can extend for hundreds of kilometres,” said Hong.

Carriers were forced to move to 40G ports on their core routers when the size of the Internet Protocol data flows did not allow them to utilize their 10G ports efficiently. 100G ports will undoubtedly handle these large flows more efficiently.

RACHEL WON

Shanghai Everbright Convention and Exhibition Center in China housed 800 attendees from all over the world.

“100G transport can support 10G, 40G and 100G client signals for applications from customer access to service edge, service edge to aggregation layer and