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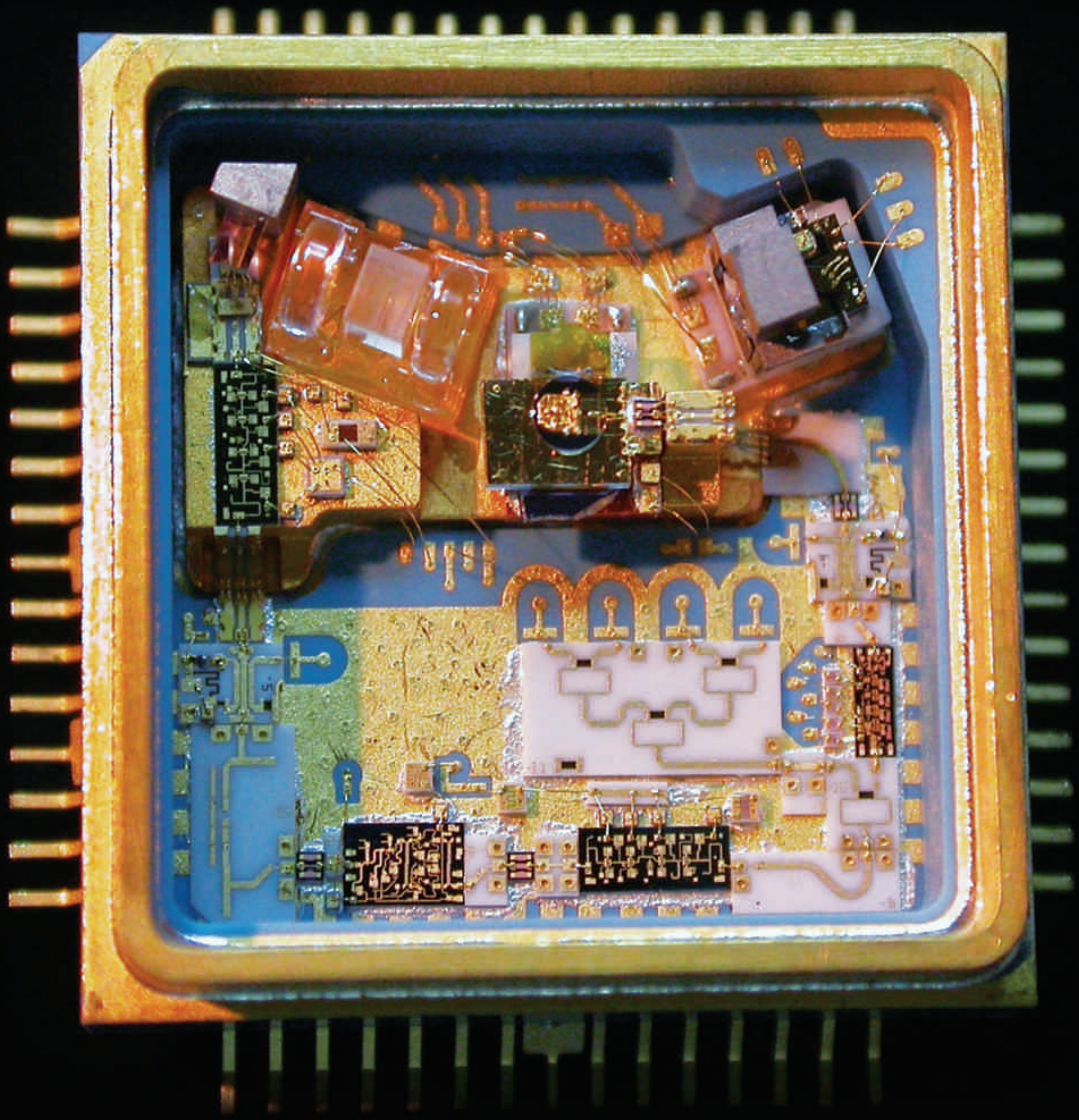
MICROWAVE PHOTONICS



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EDITORIAL
March on, not in p515
doi:10.1038/nm0511-515
The production setbacks for Genzyme's rare-disease drug Fabrazyme are tragic for the people who need the medicine. But a petition to break the company's patent exclusivity could do far more harm than good.
Full Text | PDF

NEWS AND VIEWS
Window of opportunity for daclizumab pp545 - 547
Kimberly S Schluns
doi:10.1038/nm0511-545
Full Text | PDF
See also: Article by Wuest et al.

Shedding LIGHT on severe asthma pp547 - 548
Thomas A Wynn and Thirumalai R Ramalingam
doi:10.1038/nm0511-547
Full Text | PDF
See also: Article by Doherty et al.

ARTICLES
Maternal Behavior is Impaired in Female Mice Lacking Type 3 Adenylyl Cyclase Open
Zhenshan Wang and Daniel R Storm
Neuropsychopharmacology 36: 772-781; advance online publication, December 8, 2010; doi:10.1038/npp.2010.211
Abstract | Full Text | PDF | Supplementary information

Treatment of patient tumor-derived colon cancer xenografts by a TRAIL gene-armed oncolytic adenovirus FREE
W Zhou, H Zhu, W Chen, X Hu, X Pang, J Zhang, X Huang, B Fang and C He
Cancer Gene Ther 18: 336-345; advance online publication, December 24, 2010; doi:10.1038/cgt.2010.83
Abstract | Full Text | PDF

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Long live radio

The fortuitous combination of maturing capabilities, falling component prices and rising demand bodes well for the future of microwave photonics and radio-over-fibre technologies, according to opinions gathered in this month's Technology Focus on the topic (see page 724).

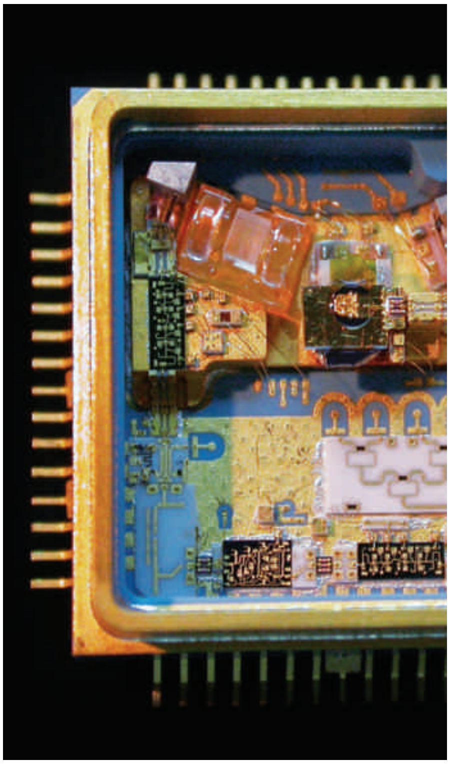
Initially inspired and driven by the military for battlefield applications such as radar and high-speed secure communications, radio-over-fibre technology is now increasing being used to provide high-speed wireless data services in civilian structures such as shopping malls, hospitals, stadiums, power plants and other large buildings. Zinwave, a start-up currently commercializing radio-over-fibre technology developed at universities in the UK, is building a growing business on this opportunity (see page 726).

Although the future of telecommunications is often described as being a completely digital world, it should not be forgotten that optical fibre is also an attractive and capable conduit for transporting high-frequency analog signals. Indeed, the use of optical fibre rather than coaxial cable — the traditional means of carrying radiofrequency signals — has some compelling benefits. For a start, the attenuation of optical fibre is typically only $0.1\ \mathrm{dB\ km^{-1}}$, which is around 3,000 times lower than coaxial cable. Second, optical fibre is considerably less bulky and far lighter in weight than coaxial cable, which simplifies the installation process.

The attraction of this technology doesn't end with the optical fibre. Optoelectronic and photonic devices such as lasers, microring and whispering gallery mode resonators and interferometers can be used to generate and process high-frequency radiofrequency signals that cannot easily be produced directly in the electronic domain (see pages 728 and 731). Many researchers are now striving to create integrated optical circuitry that can perform such tasks on the chip-scale, thus simplifying the mass-production and packaging stages.

One thing is for certain: despite the popularity of digital data formats, radio transmission is alive and kicking. ❐

CONTENTS



OEWAVES

COVER IMAGE
Close-up of the optoelectronic oscillator technology developed by US firm OEwaves.

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Wireless future drives microwave photonics

Microwave photonics is the vibrant and somewhat niche field that marries the high-frequency and analog nature of radio signals with the low-power requirements and better processing capabilities of optics. Many companies operating in this field expect the market to grow as manufacturing capabilities continue to improve and costs come down.

"There's quite a number of applications that have emerged in the past few years, both commercial and military," says Arthur Paolella, CEO of Artisan Laboratories in the US, which builds optical transmission systems for sending radiofrequency (RF) and microwave signals of up to 40 GHz over optical fibres.

The defence sector, for instance, is a big customer for Artisan. "Military systems are very wideband. Companies are trying to pump a lot of data through these systems," Paolella points out. Trying to push such high-frequency signals directly through coaxial cable would require significant power and suffer from considerable losses. "One of the key attractions of 'radio over fibre' systems is that the losses are of the order of 0.1 dB km^{-1}, whereas in coaxial cable the losses are nearly 1 dB for every 30 cm," he explains.

Many types of military hardware rely on sending and receiving high-frequency RF signals. For example, antennas are found on the tips of aircraft wings, unmanned aerial vehicles, aircraft carriers and orbiting satellites. In environments such as these, there is neither enough space nor enough electrical power for the equipment to convert the analog RF signal to the digital signal formats used by traditional optical telecommunications systems. Encoding the analog signal onto a light beam makes it possible to put bulky, complex equipment in a more convenient location at the end of a link, where signal processing can be performed.

This advantage is not only useful for distributing signals around environments as big as aircraft carriers, but it is also appealing for customers who want to place antennas in remote locations, such as the satellite farms that transmit signals to communications satellites. Edward Ackerman, vice president of research and development at Photonics Systems in Billerica, Massachusetts, USA, says that radio astronomy is one market for his company's microwave photonic links. Indeed, links manufactured by Photonics Systems are now used in the SETI Institute's Allen Telescope Array.


ISTOCKPHOTO / VILEDEVIL

Optical fibre has another important advantage over electrical wiring: it weighs only 2 kg km^{-1}. Coaxial cable, in contrast, weighs around 560 kg km^{-1}. This property makes optical fibre attractive for use in aircraft, satellites and cell-phone towers, says Paolella. Instead of using a thick and heavy bundle of coaxial cables, telecommunications companies can use a far thinner, lighter collection of optical fibres to carry the analog signal to the ground.

"The first phase of microwave photonics is building a system to send signals along the fibre, and the second is performing analog processing of the signal," says Lute Maleki, president and CEO of OEwaves in Pasadena, California, USA. Many companies have the ability to build filters, oscillators and down-converters. "You can do things using optical techniques that you cannot do directly in the electronic domain," Maleki says. For instance, the high spectral purities achievable by modern oscillators allow users to squeeze more channels into a single band than ever before, thus increasing the amount of data that can be sent without raising costs. "Everybody's interested in transmitting multigigabits of information wirelessly," he says.

Paolella believes the market for microwave photonic equipment is likely to grow with consumer demand for wireless gigabit services. The IEEE standard WiMAX (the Worldwide Interoperability for Microwave Access) was recently upgraded to handle data rates of 1 Gbit s^{-1}, and Paolella believes many small, WiMAX-based stations — known as picocells — will soon start to spring up. "With the proliferation of tablets devices such as iPads, you're going to need a lot more wireless infrastructure," he says. He also believes the demand for microwave photonics will be driven by the growth of fibre links directly to the home.

According to Paolella, the market has benefited significantly from the tenfold drop in component costs seen over the past decade. This price reduction has come about as components have become more highly integrated, although there is still room for improvement. Meanwhile, the technology has also improved. The semiconductor lasers that provide the optical carrier signal for the fibre have increased in power and now exhibit narrower linewidths, thus allowing for higher signal fidelities. Improvements have been made in photodetector efficiency and the sensitivity of the modulators used to encode the RF signal onto the optical carrier. In addition, says Ackerman, the industry has developed better ways to model the whole chain of components, which has led to better system design.

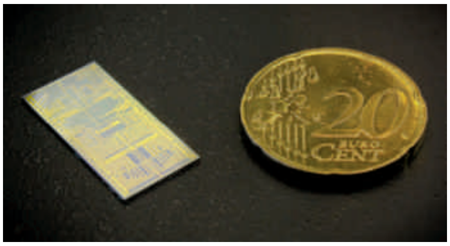
Despite such progress, development has been hampered by the recent decision of the US Defense Advanced Projects Research Administration (DARPA) to pull back on funding. "Unfortunately, for reasons that are not very clear, DARPA has severely curtailed the number of programmes that go into microwave photonics, really at a bad time," Maleki explains.

One area of the market still has much room for improvement — cost. "Price sensitivity is the parameter that is keeping microwave photonics from becoming more embedded in commercial systems," Maleki says. Ackerman agrees: "It has to be about getting things cheaper." One effort that might help to bring costs down is the development of silicon photonics. Building photonic components using silicon and the CMOS fabrication technology used to make computer chips should help make the technology cheaper and easier to integrate with future electronics.

The roll out of high-speed wireless networks is likely to drive the adoption of microwave photonic technology. ❐

On-chip signal processing

Opt. Express **19,** 21475–21484 (2011)


MAURIZIO BURLA

Reconfigurable optical delay lines (ODLs) and tunable, wideband phase shifters are important for microwave photonic applications such as signal filtering and arbitrary waveform generation. The common limitation of existing approaches is the trade-off between maximum achievable delay, operating frequency and bandwidth. Maurizio Burla and co-workers from The Netherlands have now presented a photonic signal processor that not only offers a wideband and fully tunable ODL, but is also monolithically integrated on a single compact CMOS-compatible chip. The processor consists of a reconfigurable ODL, a separate carrier tuning unit and an optical sideband filter. The optical sideband filter — a Mach–Zehnder interferometer loaded with an optical ring resonator in one of its arms — removes one of the radiofrequency sidebands of a double-sideband intensity-modulated optical carrier. The ODL and separate carrier tuning unit are individually implemented using a pair of cascaded optical ring resonators. Varying the group delay of the signal sideband by tuning the resonance frequencies and the coupling factor of the optical ring resonators in ODL, while also applying a full 0–2π carrier phase shift in separate carrier tuning, allowed the researchers to demonstrate a two-tap microwave photonic filter whose notch position can be shifted by 360° over a bandwidth of 1 GHz. *RW*

Comb-based pulse shaping

IEEE Photon. Tech. Lett. **23,** 1618–1620 (2011)

Microwave photonic filters offer attractive features such as low loss, low sensitivity to electromagnetic interference, and rapid tunability and programmability over large bandwidths. Most of them are based on multiple physical delay lines — a concept that is difficult to scale to large numbers of taps. Recent work has used broadband light sources and a single dispersive element. Because the medium introduces a differential delay between optical frequencies, the multiple optical frequencies function as multiple taps, thus avoiding the use of many physical delay lines. Andrew Weiner and co-workers from the USA now demonstrate a reconfigurable and tunable flat-top microwave photonic filter using an electro-optic frequency comb and a dispersive medium, in which each individual optical frequency component in the comb becomes an independent filter tap. They implemented a flat-top filter by applying positive and negative weights across 32 comb lines, and tuned the filter central frequency by adding a phase ramp to the tap weights. The scheme provides flexible and tunable filter characteristics by programming the amplitude and phase of individual comb lines using an optical line-by-line pulse shaper. The researchers say that increasing the number of comb lines may provide lower pass-band ripple, narrower transition bands and stronger sidelobe suppression. *JB*

Scaling down frequency

J. Lightwave Technol. **29,** 3091–3098 (2011)

Although directly sampling an electric field at optical frequencies is impossible owing to the frequency limitation of electronic sampling devices, indirect sampling can be achieved through heterodyne processes that generate beat notes in the radiofrequency domain. Peter Delfyett and co-workers in the USA have now used frequency combs as local oscillators to downconvert and compress optical signals through multiheterodyne detection, a process by which two combs that share an optical reference are mixed to deduce the effect of a medium on the signal comb. The researchers used a commercially available 250 MHz erbium-doped fibre frequency comb as a local oscillator in three distinct experiments: mixing two mutually incoherent mode-locked laser combs; mixing a mode-locked comb and phase-modulated continuous-wave light; and performing spectral interferometry on downconverted white light. The researchers demonstrated spectral compression by factors of 1,600 for phase-modulated light and 17,000 for mode-locked pulses, during which carrier frequencies were converted from ~200 THz to ~100 MHz. They also showed that interference patterns can be obtained in the microwave regime by summing photocurrents, and that these patterns can be used for high-resolution white-light spectral interferometry. *DP*

Waveform mathematics

Opt. Lett. **36,** 3557–3559 (2011)

Many tasks in signal processing severely stretch or are beyond the capabilities of electronic circuitry. The ability to perform such signal processing tasks on high-frequency microwave waveforms, therefore, is one of the key attractions of microwave photonic devices. One of the latest devices to demonstrate this ability is a photonic temporal integrator developed by José Azaña and co-workers in Canada. The device uses a superluminescent diode, a semiconductor optical amplifier, an electro-optic modulator and a cascade of fibre interferometers to generate an output signal that is the cumulative temporal integration of an arbitrary input waveform. The microwave signal to be integrated is used as the drive signal for the electro-optic modulator and the output of the calculation is an optical signal that is collected by a photodetector connected to a sampling scope. Tests show that the device can accurately process signals with bandwidths of ~36 GHz over a measurement time window of 4 ns, thus significantly outperforming electronic technologies. Such integrators are required for applications in computing, control and communications networks. *OG*

Ultralow phase noise

Opt. Lett. **36,** 3260–3262 (2011)

Microwave signals with low phase noise are important for applications such as large-scale high-precision remote synchronization and long-baseline interferometry. It has been shown that an ultralow phase noise of −104 dBc Hz^{-1} at an offset of 1 Hz from a 10 GHz carrier can be generated by a Ti:sapphire-based optical frequency divider (OFD). Achieving this noise level using an erbium-doped fibre-based OFD would allow large-scale pulse distribution at telecommunications wavelengths. Scott Diddams and co-workers in the USA have now presented a scheme that is capable of producing 10 GHz microwave signals with absolute phase noise below −100 dBc Hz^{-1} at an offset of 1 Hz, limited by the optical frequency reference. For frequencies of >10 kHz, the phase noise is shot-noise-limited to −145 dBc Hz^{-1}. The key component of the scheme is a 200 MHz erbium-doped fibre mode-locked laser with a high-speed intracavity electro-optic phase modulator and low intrinsic relative intensity noise. The team achieved a phase noise that is equal to or better than the 10 GHz phase noise from cryogenic microwave oscillators and is more than 40 dB lower than 10 GHz room-temperature oscillators at an offset frequency of 1 Hz. *NH*

Written by James Baxter, Oliver Graydon, Noriaki Horiuchi, David Pile and Rachel Won.

Covering all bases

The popularity and demand for data-rich wireless communication is driving the deployment of radio-over-fibre technology and the success of the firms such as Zinwave, reports **Nadya Anscombe**.

Many new companies fail because of bad timing. Often the company has a great product but it is simply launched either before there is sufficient market demand or after its competitors have already taken a large share of the market. But sometimes, if you are lucky, everything falls into place at the right time. UK firm Zinwave, which launched its first product onto the market in 2007, believes its success over the past four years was largely due to having "the right product at the right time", according to its president of international sales, Colin Abrey.

Zinwave was founded to commercialize in-building wireless technology for high-speed data communication based on radio-over-fibre (RoF) technology licensed from Cambridge University and University College London. By encoding radiofrequency (RF) signals onto light beams travelling down an optical fibre, RoF avoids the problems of loss and limited bandwidth traditionally associated with transmitting RF signals down coaxial cable.

"With the number of frequency bands being used by wireless services multiplying every year and 4G networks just around the corner, the industry needs a technology that can support all these different frequencies as well as future ones," Abrey explained to *Nature Photonics*. "Our technology can do this."

Zinwave claims its active distributed antenna system (DAS) is the only technology that supports all services in the frequency range of 150–2,700 MHz on a single hardware layer. "Our system is agnostic of protocol, modulation scheme and frequency," says Abrey. "This means that on multiservice projects — projects requiring three or more services — we are very cost-effective when compared with our competitors' systems, which require the customer to buy service-specific hardware that increases the system cost with each additional service. It also means that our technology is future-proof because you can add any service onto the existing system."


ZINWAVE

Zinwave's broadband radio-over-fibre technology is independent of frequency, modulation and protocol.

This flexibility is enabled by the amplification and distribution architecture Zinwave has built around its RoF technology. The amplifiers and other active components must be of sufficient quality in terms of their linearity, dynamic range and bandwidth to allow any number and type of service to be transmitted without noticeable distortion. One crucial aspect of Zinwave's system design is to keep the transmission and receiving electronics spatially and electrically separate, which eliminates the need for filters. Service and frequency discrimination is then provided not by Zinwave's system but by the base-stations that are connected to it.

Although innovative electronics is what now differentiates Zinwave from its competitors, it was innovative photonic technology that enabled the company to start up in 2002. Zinwave was founded on the idea that cheap, uncooled laser diodes were a viable alternative to the expensive cooled lasers that were in use by other RoF companies. Researchers at Cambridge University and University College London found that uncooled, directly modulated distributed feedback laser diodes could provide the linear performance required for high-quality analog RF signal transmission over modern broadband wireless services. This discovery allowed Zinwave to develop systems at considerably lower costs than its competitors.

"We have benefited from the development of uncooled laser diodes for digital modulation at 10 Gbit s^{-1} for use with the gigabit Ethernet standard," explains Andy Bell, Zinwave's CTO. "We needed lasers with high linearity, large modulation bandwidth and excellent high-temperature performance, and these devices became available to us just at the right time."

Although these types of lasers are now freely available, the key to using them correctly is choosing the correct system power. Greater laser output powers support larger coverage areas, but uncooled lasers are limited in their power capabilities. For this reason, Zinwave opted for a medium-power system with a large number of antennas (up to 64 per hub) to ensure optimum coverage. "We use 100 mW power amplifiers, and this is pushing the limits of what is possible with uncooled laser diode technology," says Bell.

Zinwave's original research also suggested that the performance of vertical-cavity surface-emitting lasers (VCSELs) — another type of uncooled semiconductor laser — would also be sufficient for many broadband applications. Although this would further reduce the cost of Zinwave's products, Bell says the company has not yet found a commercial VCSEL with the required performance characteristics. "We want to use VCSELs but have not yet found a device with a good enough signal-to-noise range or dynamic range for our application," said Bell. "The performance of VCSELs is not there yet, but it is moving in the right direction.

I would like to think that in the next couple of years our products could be using VCSELs instead of distributed feedback lasers."

The research also showed that it is possible to use multimode fibre (MMF) instead of more expensive single-mode fibre (SMF). "This not only makes our technology independent of protocol, modulation scheme and frequency, but also means we can use any type of fibre," said Bell. "This allows our technology to be used with older MMF without the need to install new, expensive fibre."

One case study that illustrates the benefits of RoF technology is a nuclear power station in the USA that required wireless coverage in multiple buildings totalling an area of around 500,000 square feet. As well as requiring multi-operator cellular services, paging and public safety radio services, the company also wanted to integrate a 900 MHz wireless remote dosimetry monitoring system that would continuously transmit staff exposure levels and sound an alarm if any staff were in danger.

"Every industry has different drivers, and in this case the company needed to utilize its existing MMF by using multiple patch panels and ST optical connectors, which Zinwave's DAS supports effectively," said Bell. "There was therefore no need for the considerable expense of installing new SMF or new angle-polished connectors, which would have been required with other candidate DAS solutions. Even we were surprised that the system worked so well, considering that the company's MMF was installed in the 1960s."


ZINWAVE

Zinwave's Andy Bell.

ZINWAVE

Zinwave's technology relies on uncooled laser dioes to achieve cost-effective operation.

Although this case study demonstrates the flexibility of Zinwave's product, Bell and Abrey admit that it is a particularly niche application, and that most of Zinwave's customers want to use SMF instead of MMF. "Our company was set up at a time when SMF was much more expensive than MMF and people were looking for ways to use their old MMF," says Abrey. "The in-building market today is using an awful lot more SMF than it did ten years ago. Most of our installations are for new buildings or refurbished buildings, and our customers are happy to use SMF."

Zinwave has now installed deployments all over the globe across markets that include healthcare, hospitality and retail. For example, the company has provided in-building coverage for the Westfield shopping centre in Sydney, Australia, where Zinwave's 3000 DAS solution supports all major operators while also providing personal mobile radio services for all the mall staff.

This ability to carry a frequency range that includes radio is particularly attractive to the healthcare market, where staff such as paramedics and police require radio coverage inside large hospital buildings. "Deployment in hospitals is one of our fastest growing sectors," says Abrey. "There is a growing acceptance that cellular services do not affect medical equipment as they used to and senior staff want mobile phone coverage as well as radio coverage inside a hospital."

These are just some of the current market drivers that have enabled Zinwave to grow from humble beginnings to 25 employees spread across the UK, the USA and Australia.

Further growth will require the company to embrace new technologies. For example, using free-space optical links instead of fibre links would make installation even simpler. "It would be ideal if, to install our system, all you had to do was clip a small unit onto the ceiling of an office," said Bell. "But to make this a reality we would need class-1 lasers with the right performance to enable a link with sufficient bandwidth and quality. We would also need to be able to target the lasers with extreme accuracy, and all this is a long way off."

Another idea that may be closer to reality is to make the system independent of building design. "We want to eliminate the need for a site walk and RF planning," said Bell. "All modern buildings these days have integrated structured cabling systems, and we are looking at how DAS can exploit this in a similar way to existing WiFi deployments. Specifically, we believe a rules-based approach to antenna deployment, together with a plug-and-play architecture, will allow both craft-free initial deployment and simple future expansion. This would enable wireless services to be installed at the construction phase in a similar way to a sprinkler system — an idea that we like to call the 'fifth utility." ❐

Nadya Anscombe is a freelance journalist based in the United Kingdom.

SOURCES

The optoelectronic oscillator

Lute Maleki

Photonic technology can now be used to construct miniature sources of high-frequency radio waves that have exceptional spectral purity.

In the early 1980s, researchers at NASA's Jet Propulsion Laboratory in California realized that stable reference signals generated by a hydrogen maser atomic clock could be distributed over optical fibres to multiple antenna sites at NASA's Goldstone radio telescope facility in the Mojave Desert. The idea was to reduce the high cost of installing and maintaining hydrogen masers at each antenna site by instead delivering radiofrequency (RF) reference signals from a single site to multiple users located tens of kilometres apart. However, such a long separation distance could not be served by coaxial cables — the usual choice for transmitting RF signals — as the loss of the system would be too high for practical use. Scientists instead decided to encode the RF signals onto light using lasers, modulators and low-loss optical fibre, which were rapidly finding widespread applications in optical communications. The signal distribution system at the Goldstone complex also provided the first example of an operational RF photonics link, in which RF, microwave or millimetre-wavelength signals are carried as modulation data on an optical carrier.

Subsequent work in the field of RF photonics at the Jet Propulsion Laboratory focused on developing other capabilities that could take advantage of the unique properties of optical components. One area of research pursued the realization of a microwave oscillator based on RF photonics. Oscillators are devices that produce periodic waves whose amplitude, phase and frequency can be precisely controlled to produce signals that carry information. Oscillators are an essential element in any system that receives or transmits a signal, and are widely used in communications systems, radar, signal processing, sensors, metrology, radio astronomy and a myriad of other applications where an electromagnetic signal is generated, received or processed.

Demanding applications require oscillators of very high spectral purity — systems capable of generating a near-perfect sinusoidal signal. The spectral purity of an oscillator is governed by the loss in its feedback circuit. To achieve the ultrahigh spectral purity levels required by advanced metrology, communications, radar and data transmission systems, oscillators with high-quality-factor (*Q*-factor) resonators are used to minimize the dissipation of energy circulating in their feedback loop. Piezoelectric quartz resonators, thanks to their extremely high *Q*-factors in the frequency range of 10–100 MHz, are particularly suitable for use in RF systems. As the frequency of the output is increased, the *Q*-factor of the electronic resonator degrades and the spectral purity deteriorates. Thus, for microwave and millimetre-wavelength applications in the gigahertz region, the best signals are generated with a multiplied output from a high-performance quartz oscillator operating in the megahertz range. However, this frequency multiplication process also multiplies the oscillator noise, which means the performance of microwave and millimetre-wavelength oscillators based on frequency multiplication will always degrade with increasing frequency.

Researchers at the Jet Propulsion Laboratory then decided to focus on the development of an alternative solution: a new type of high-performance oscillator known as the optoelectronic oscillator (OEO; Fig. 1). The OEO is based on the use of optical waveguides and resonators, which exhibit significantly lower loss than their electronic counterparts. In a typical OEO, light from a laser is modulated and passed through a long length of optical fibre before reaching a photodetector. The output of the photodetector is amplified, filtered, adjusted for phase and then fed back to the modulator. This feedback loop can generate self-sustained oscillation if its overall gain is larger than the loss and the circulating waves can be combined in phase.

The OEO architecture is quite versatile and can be configured to customize performance in a variety of

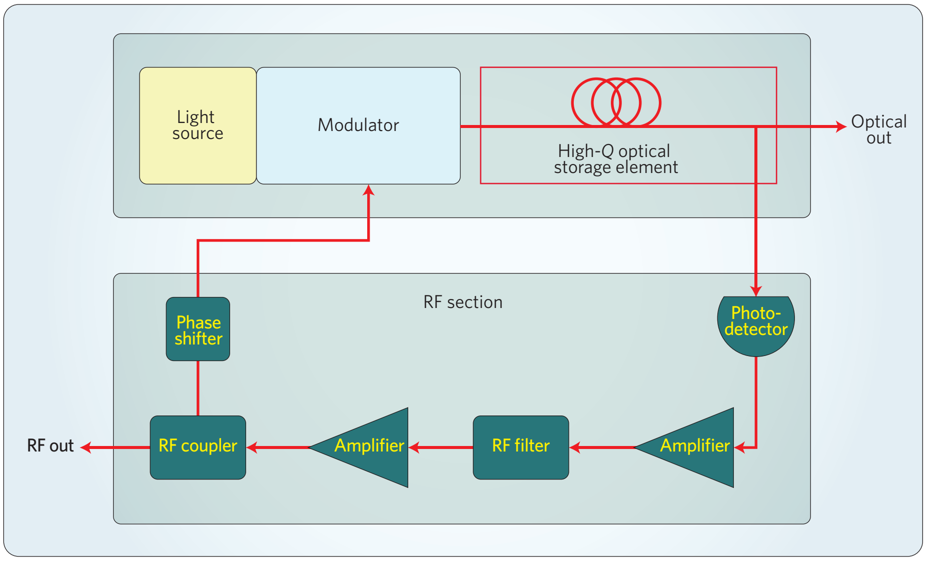


Figure 1 | Block diagram of a generic OEO.

ways using different optical and electrical components. The gain element, filter and phase shifter can be placed either in the optical segment or the electrical segment of the loop. The laser may be of any suitable type and wavelength, and the RF modulation can be achieved directly, for example by controlling the current applied to a semiconductor laser, or with an external modulator. Modulation of phase, amplitude or polarization can all be employed and the high-*Q* (low dissipation loss) optical cavity can be a Fabry–Pérot, whispering gallery mode resonator (WGMR) or long fibre delay with a *Q*-factor corresponding to its length. The operating frequency can be either fixed using a filter or tuned by changing the wavelength of the laser or the cavity's optical path length. Finally, the circulating light can be generated either by a laser external to the loop or in an optical loop whose optical gain can be coupled to the electrical loop through the modulator — a configuration known as the coupled optoelectronic oscillator. Researchers in a number of groups around the world have demonstrated OEO operation with such configurations at various radio, microwave and millimetre-wavelength frequencies.

The spectral purity of the signal in the OEO is directly related to the *Q*-factor of the loop. Most OEOs still utilize a long length of fibre to achieve high spectral purity. Indeed, the most spectrally pure 10 GHz oscillator demonstrated so far utilized a 16 km fibre loop. A disadvantage of using a fibre loop is the production of 'super modes' that appear in the phase noise spectrum. These modes — highly undesirable for certain applications — are caused by the propagation of waves multiple times around the OEO loop.

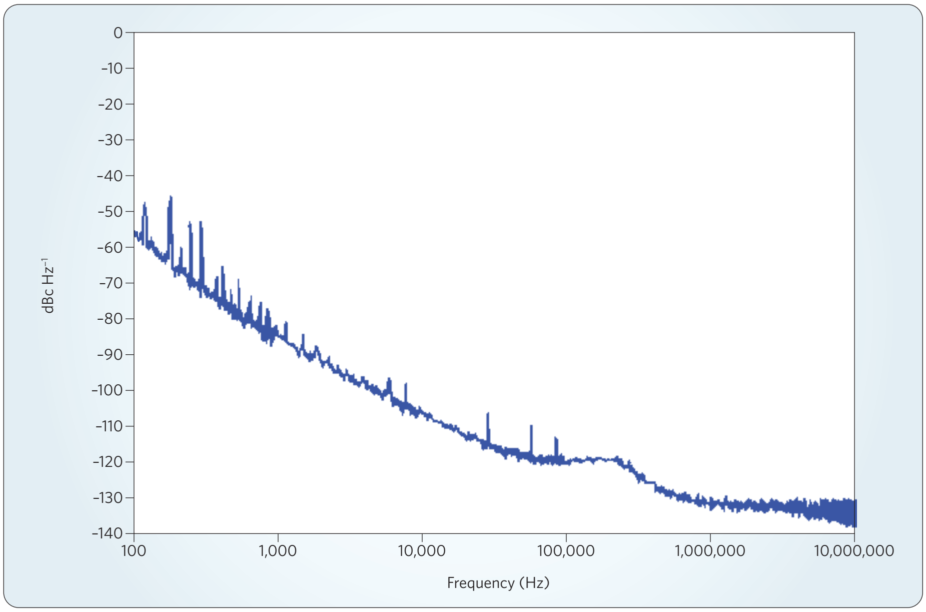
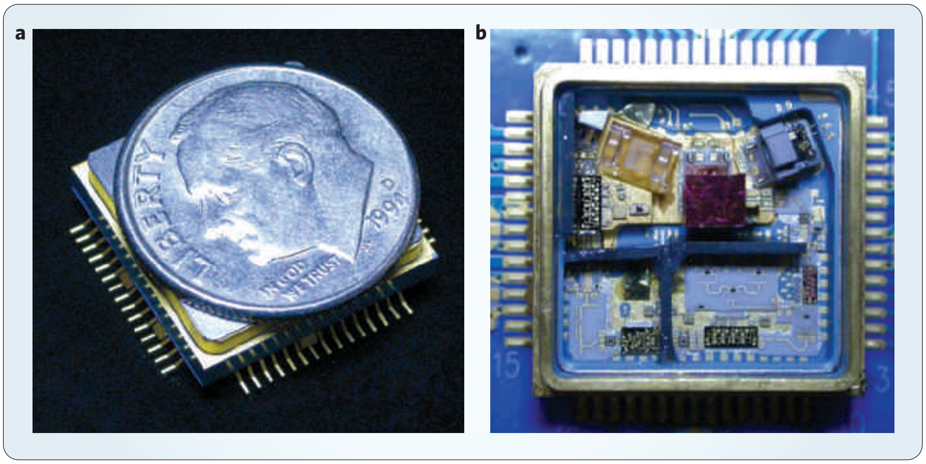


Figure 3 | Phase noise of a miniature 30 GHz OEO.

There are two effective photonic remedies for the removal or suppression of super modes. One scheme involves using multiple loops of fibre, which together essentially function as a narrowband filter. Another technique is to use a high-*Q* optical cavity to filter out the unwanted modes. Although Fabry–Pérot cavities with high *Q*-factors are useful for achieving this, a more convenient choice is ultrahigh-*Q* WGMRs.

WGMRs ranging in size from a few hundred micrometres to a few millimetres can be fabricated from a wide variety of optically transparent materials. In particular, WGMRs made from crystalline materials can have *Q*-factors in excess of a billion, with the largest reaching 3×10^{11}. The bandwidths associated with such *Q*-factors are narrow enough to provide an effective remedy for removing unwanted super mode noise in the OEO spectrum.

Recently, a number of communications, data processing and radar applications have emerged that require high-performance microwave and millimetre-wavelength oscillators that not only are of miniature size but also have power consumptions many orders of magnitude lower than existing devices. This is a growing need, and optical oscillators based on WGMR technology are currently the only available solution. In particular, OEOs utilizing high-*Q* WGMRs made from an electro-optic material can provide high performance in a package smaller than a coin (Fig. 2). In this configuration, the resonator, excited with light from a semiconductor laser, serves both as the high-*Q* element and as the modulator in the OEO loop. The free spectral range of the resonator, which is related to its size, determines the frequency of the signal produced by this miniature OEO. This configuration can produce 30 GHz output signals with higher spectral purity than alternative high-power approaches. Oscillators based on this architecture are particularly desirable when high spectral purity is required in a small form factor at frequencies in the range of 10–40 GHz and higher (Fig. 3). These devices have already found applications in small military platforms and will soon enter commercial products such as broadband wireless communications systems.



OEWAVES

Figure 2 | Miniature OEO based on a lithium niobate WGMR.

US firm OEwaves recently introduced an oscillator design based on the use of Kerr optical frequency combs. Kerr frequency combs are generated by exciting a single mode of a miniature WGMR with light from a continuous-wave laser. Sidebands around the excited mode are generated when the intensity of the light is such that a four-wave mixing process can be excited in the resonator material. By increasing the applied optical power, a cascade effect produces a series of sidebands that form a frequency comb. The comb is essentially a series of phase-locked lasers separated in frequency by the resonator's free spectral range. It can be demodulated by a fast photodiode to produce a signal that is the product of the beating between the comb lines. Owing to the high degree of coherence and the large number of comb lines, the spectral purity of the beat frequency is extremely high.

Because optically transparent crystals such as calcium fluoride and magnesium fluoride can be used to produce ultrahigh-*Q* WGMRs, small semiconductor lasers emitting just a few milliwatts of power can excite nonlinear interactions and thus produce Kerr combs and associated RF signals. This architecture provides a simple, robust and efficient scheme for generating microwave and millimetre-wavelength signals in a tiny form factor.

An attraction of the resonator-based OEO architecture is that it is amenable to on-chip integration. An early programme run by the Defense Advanced Research Projects Agency (DARPA) in 2006 successfully combined an external resonator with a photonic chip fabricated on the silicon-on-insulator platform. The performance of the oscillators produced through this approach was limited by the noise performance of the electronic amplifiers fabricated by the CMOS process. Currently, a new DARPA programme aims to produce a 20 GHz oscillator with exceptionally high spectral purity based on an electronic–photonic heterogeneous integration process. Once demonstrated, such a chip-scale oscillator will be available with unmatched performance for applications across a wide variety of fields. ❐

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MICROWAVE PHOTONICS

Harnessing slow light

José Capmany, Ivana Gasulla and Salvador Sales

Slow-light techniques originally conceived for buffering high-speed digital optical signals now look set to play an important role in providing broadband phase and true time delays for microwave signals.

For the past 25 years, microwave photonic (MWP) systems and links have relied almost exclusively on discrete optoelectronic devices (semiconductor lasers and pin photodetectors) as well as standard optical fibres and fibre components (couplers, isolators, power dividers and multiplexers). These technologies have been used to support well-known traditional radiofrequency transmission techniques such as linearization, mixing, intermediate frequency up- and downconversion and subcarrier multiplexing.

However, the deployment of converged access networks, which marry the concepts of radiofrequency and optical networking, would greatly benefit from the development of MWP technologies offering greater functionality and chip-scale integration. Two approaches to tackling this task — slow- and fast-light (SFL) techniques — have made considerable progress in recent years.

SFL techniques aim to control the group velocity of an optical signal propagating in a particular device or medium. The propagation of a time-varying light signal through a dispersive optical medium implies that each of its frequency components will travel with a different phase velocity, resulting in an overall envelope time shift that is inversely proportional to the group index of the material n_g, which in turn depends on the dispersion of the refractive index, dn/dω. A slow-light medium is one that exhibits normal dispersion ($v_g \ll c$) which is achieved by forcing dn/dω to be large and positive. In contrast, a fast-light medium is one that exhibits anomalous dispersion ($v_g \gg c$).

Several nonlinear effects have been proposed as techniques for implementing SFL devices, including electromagnetically induced transparency in cold atoms, stimulated Brillouin and Raman scattering in optical fibres, coherent population oscillation in semiconductor waveguides, photonic crystals, dispersion-compensating fibres, fibre Bragg gratings and coupled cavities. All of these schemes can be characterized by a common feature: the existence of either a single or multiple resonances. An absorption or gain resonance can be provided by a simple atomic transition or, in the case of a microresonator or Bragg grating, using nonlinear processes such as resonant scattering, spectral hole burning or four-wave mixing.

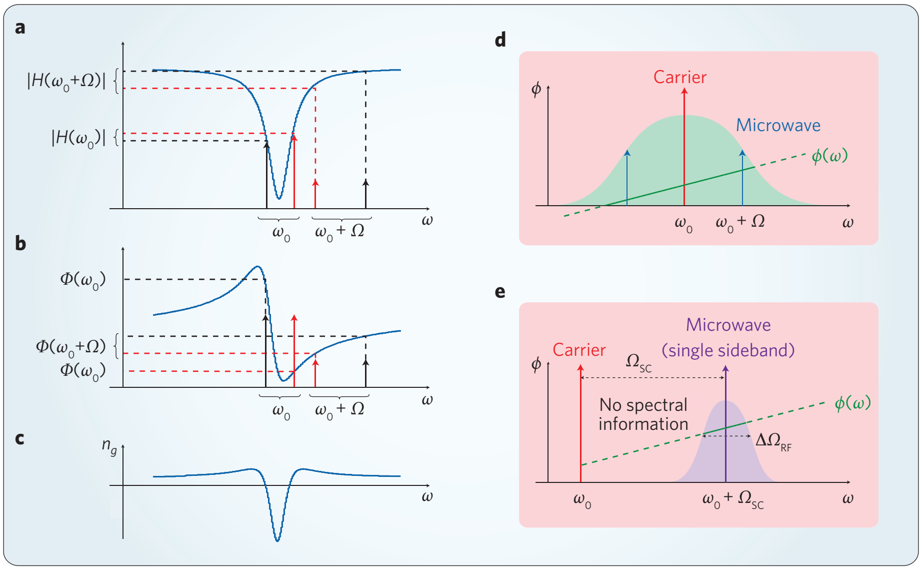

Figure 1 | Implementation of tunable phase shift and true time delay in a photonic resonant medium. **a**–**c**, The Lorentzian amplitude (**a**) and phase (**b**) responses that characterize a photonic resonant medium give rise to a large variation in the material's group index n_g (**c**). Implementing a microwave phase shifter (black arrow) or a true time delay (red arrow) requires the optical carrier ω_0 and the radiofrequency subcarrier $\omega_0 + \Omega$ to be in different spectral locations. **d**, Phase shift response of the resonance; narrowband true time delay. **e**, The separate carrier tuning technique; broadband true time delay.

Originally conceived for buffering high-speed digital optical signals, SFL techniques are now being employed to provide broadband phase delays and true time delays for microwave signals. Tunable control over phase delay is essential for the implementation of broadband MWP reconfigurable filters such that varying the resonance position does not affect the filter's spectral period or width. Tunable control over true time delay is instrumental to the implementation of broadband phase array systems, which find applications in radar and satellite communications. Figure 1 helps to explain the differences between these two key functionalities.

Imagine, for instance, an optical signal traversing a photonic resonant medium such as a coupled resonator optical waveguide exhibiting an amplitude dip or resonance. A tunable radiofrequency phase shift can be achieved if we spectrally place this signal such that the optical carrier falls inside the resonance while the radiofrequency subcarrier stays outside. When beating occurs at the receiver, the detected signal will experience a phase shift that is determined by the phase difference between the optical carrier and the subcarrier. On the other hand, implementing a tunable true

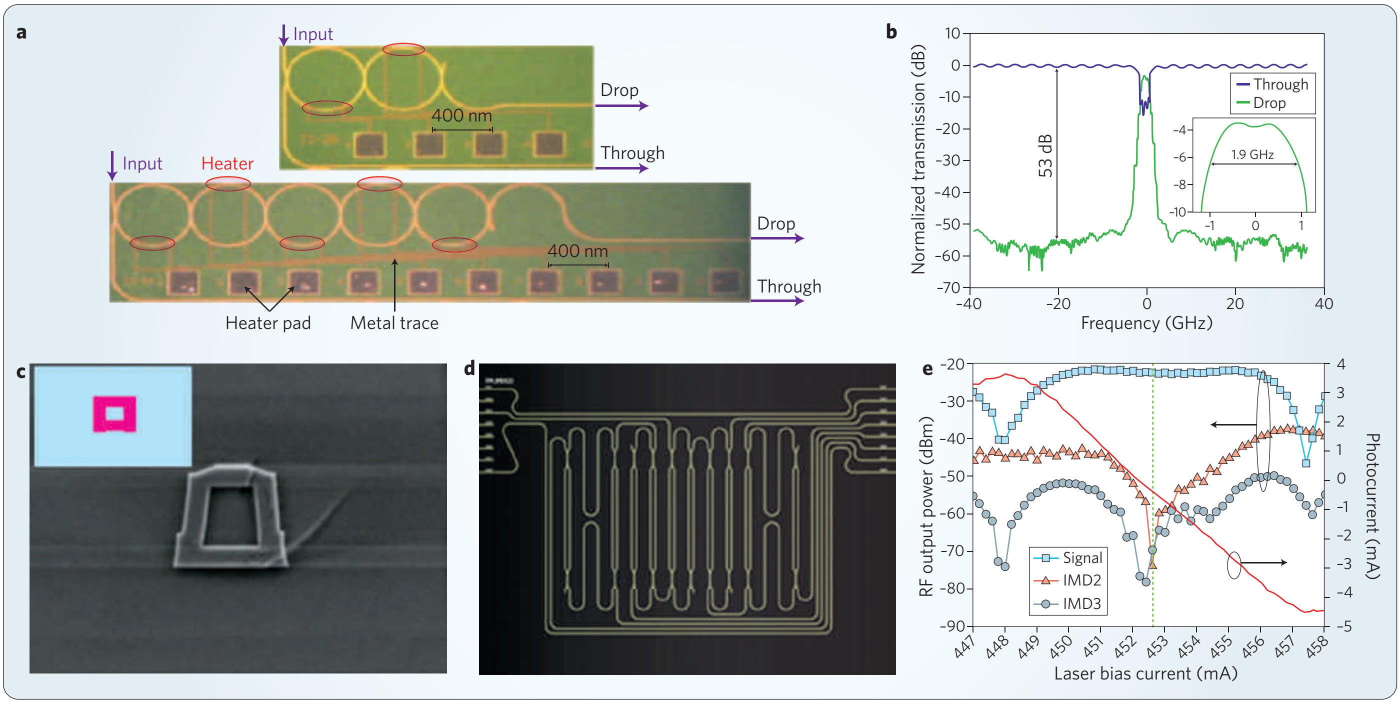

Figure 2 | Photonic integrated circuits for MWP applications. **a**,**b**, Second- and fifth-order gigahertz-bandwidth optical filters based on high-order silicon ring resonators developed by Kotura and Telcordia (**a**) with measured transfer functions (**b**). **c**–**e**, Photonics-integrated discriminator for phase-modulated MWP links implemented by researchers at the University of Twente and LioniX. **c**, Scanning electron microscope image of the TriPleX waveguide configuration. **d**, Integrated filter layout. **e**, Measured discriminator transfer function. IMD2 and IMD3 are the second- and third-order intermodulation products, respectively. Images in **a**, **c** and **d** are reproduced with permission from OSA.

time delay requires both the carrier and the modulating sideband to be located inside the resonance. In both schemes, a variation in the spectral position of the optical carrier provides the desired tunability of either the phase shift or the delay imposed upon the detected radiofrequency signal.

Unfortunately, achieving a true time delay suffers from the same limitation experienced when buffering digital optical signals: SFL systems have a trade-off between the achievable time delay and bandwidth. In the case of MWP systems, an elegant solution known as separate carrier tuning was proposed by Paul Morton and Jacob Khurgin from Johns Hopkins University, Maryland, USA. This technique, which exploits the fact that most of the spectral region between the carrier and the sideband is unoccupied, requires a constant group delay only in the subcarrier region as long as an appropriate phase shift is also imposed on the carrier.

Researchers have successfully demonstrated the separate carrier tuning technique by using stimulated Brillouin scattering in fibres to produce a tunable complex-valued two-tap filter featuring a delay line with a bandwidth of 120 MHz at a central frequency of 6 GHz.

The European project GOSPEL (Governing the Speed of Light) has had notable success in developing a suite of MWP devices. In relation to broadband phase shifters for microwave signals, the use of coherent population oscillation in a semiconductor optical amplifier offers a bandwidth of several tens of gigahertz while providing small size, low weight and the possibility of on-chip integration. Tunability has been demonstrated by optical pumping or changing the electrical injection current. Researchers from the Universitat Politècnica de València (UPVLC), Spain, and the Danish Technical University (DTU) have demonstrated phase shifts of up to 360° over bandwidths exceeding 40 GHz by cascading five semiconductor optical amplifiers stages followed by three intermediate optical filters. This configuration has recently been refined to realize a full 360° tunable microwave phase shifter based on a single semiconductor optical amplifier.

Researchers at DTU have also demonstrated a tunable microwave phase shifter based on a silicon-on-insulator dual-microring resonator. The device provides a quasilinear phase shift of up to 360° with a radiofrequency power variation of <2 dB and a frequency bandwidth of 40 GHz.

Collaborators from DTU and UPVLC have also demonstrated a tunable MWP filter in the 20 GHz region based on a single silicon-on-insulator microring resonator phase shifter.

Stimulated Brillouin scattering in fibres can be exploited to realize a less compact microwave phase shifter that has the advantages of greater bandwidth and easier tuning. The first of such schemes, proposed by researchers at the Universidad Pública de Navarra (UPNA) in Spain, featured bandwidths of 20 GHz. In a recent collaboration between UPNA, UPVLC and the École Polytechnique Fédérale de Lausanne (EPFL), researchers extended the achievable bandwidth to over 50 GHz, which demonstrates potential for reaching the millimetre-wavelength region.

Several SFL-based approaches have been reported for implementing true time delays in microwave signals using photonic devices, including those based on stimulated Brillouin and Raman scattering in optical fibres, coherent population oscillation in erbium-doped fibre amplifiers, electromagnetically induced transparency in gas-filled hollow-core fibres and wavelength conversion and fibre dispersion. Microring resonators in particular have been attracting significant attention because of their compact size and opportunity for chip-scale integration. Although in isolation microring resonators provide only short delays over small bandwidths, larger bandwidths and longer delays can be achieved by placing several slightly detuned rings in a cascade, as proposed by Khurgin. Dutch firm LioniX and researchers at the University of Twente have recently used this technique to create an optical beam-forming network.

Photonic crystal waveguides based on line defects can also be used to implement true time delays. Recent work by researchers at St Andrews University in the UK shows that photonic crystal waveguides offer a better figure of merit than microring resonators at very high frequencies. French firm Thales has fabricated the first waveguides for this purpose and has also collaborated with UPVLC to develop the first implementation of MWP filters. Researchers at the University of Kassel in Germany, Technion University in Israel and DTU expect further flexibility by incorporating quantum dots to increase the achievable delay and tunability of photonic crystal waveguides. In addition, researchers at the Centre for Ultrahigh Bandwidth Devices for Optical Systems in Australia are currently working to generate long delays by enhancing nonlinear effects in waveguides.

Scientists have also demonstrated the integration of different MWP functionalities. Researchers at Twente University and LioniX recently implemented an integrated MWP filter consisting of a reconfigurable optical delay line onto a single CMOS-compatible photonic chip. A complex multicavity design (Fig. 2a,b) reported by researchers from Kotura and Telcordia features 1–2 GHz bandwidth filters with very high extinction ratios (~50 dB). The silicon waveguides employed to construct these filters have propagation losses of just ~0.5 dB cm^{-1}. Each cavity is thermally controlled by metal heaters and placed on top of the ring. With a power dissipation of around 72 mW, the ring resonance can be tuned by one free spectral range, thus resulting in a wavelength-tunable filter. Both second- and fifth-order ring resonators have been implemented so far.

In the field of signal transmission and conditioning, researchers from LioniX and the University of Twente recently demonstrated the first integrated discriminator for phase-modulated MWP links. The photonic chip in this work consisted of five optical ring resonators that could be controlled through thermo-optical tuning. The layout, shown in Fig. 2c–e, is based on waveguides implemented using LioniX's high-contrast TriPleX technology.

These examples indicate that the realization of integrated chips featuring sophisticated MWP circuitry is no longer a distant dream, but will soon become a reality. ❐

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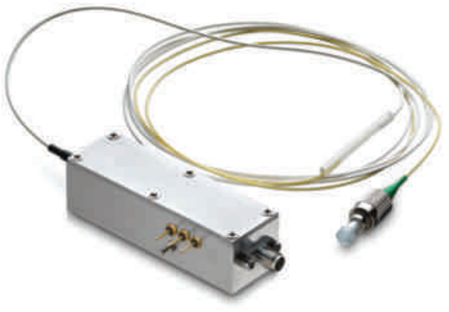
Compact devices aid integration



Microwave Photonic Systems (West Chester, Pennsylvania, USA) has released a range of new transmitters and receivers that are designed to suit incorporation into radiofrequency (RF) photonic transport subsystems. The Ultra Compact Transmitter and Ultra Compact Receiver are aimed for use in systems where size, weight and power are critical. The MP-2320, MP-5000 and MP-6000 series of RF photonic links operate across the frequency range of 5 MHz to 26.5 GHz. The transmitter comes with a bulkhead-mounted connector or a single-mode fibre pigtail, where the length of the pigtail and type of connector can be specified by the customer. Visual indicators alert the user to any faults in the system. A DB-15 interconnect powers the module and relays its status through RS-232 and RS-422 protocols. The receiver has a single-mode fibre pigtail and a replaceable SMA/F output connector.

www.b2bphotonics.com

Links promise 40 GHz bandwidth

The latest microwave photonic links from Photonic Systems (Billerica, Massachusetts, USA) operate at frequencies of more than 40 GHz. They are designed for applications such as remote antenna distribution and radio/intermediate frequency signal distribution in military systems, satellite communications and cellular base stations. The PSI 1600 series transmits analog signals at frequencies of up to 12 GHz with high dynamic range — typically better than 112 dB Hz^{-1}. The PSI 2600 series relies on lithium niobate Mach–Zehnder modulators to provide a very high dynamic range, and has an operating bandwidth of 0.045–20 GHz. Both series are available with no amplifier, a pre-amplifier, a post-amplifier, or both. The PSI 3600 series operates without an amplifier and covers a frequency range of 0.045–18 GHz. A narrowband version is optimized for operation with channel bandwidths of less than one octave within a total possible operating bandwidth of 18 GHz, providing a dynamic range of more than 120 dB Hz^{-1}.

www.photonicsinc.com

Add-on modules check fibres

The Sidelighter optical module from Artisan Laboratories (Jamison, Pennsylvania, USA) connects to most RF and microwave signal analysers, from suppliers including Anritsu, Agilent and Bird Technologies, to provide optical measurement capability for checking fibre transmission. It can be used to convert a handheld microwave analyser into a high-performance optical-distance-to-fault locator. Artisan says that its optical module does not suffer from the large 'dead zone' that is characteristic of an optical time-domain reflectometer, whose spatial resolution is limited by the duration of the optical pulses it employs. The module is designed for installing, verifying, troubleshooting and repairing fibre-optic cables and communication systems. Potential applications include aircraft, shipboard, distributed antenna and fibre-to-the-premises systems and satellite ground stations. The module allows both coaxial and fibre-optic cable measurements for hybrid systems. The device has a 5 cm event resolution, and it can resolve two events separated by less than 15 cm in a single fibre-optic cable.

www.artisanlabs.com

Low-noise phase-locked loop

An optical phase-locked loop system from Redfern Integrated Optics (Santa Clara, California, USA) is aimed at applications in RF and microwave photonics that require accuracy, reliability in demanding field conditions and high resolution. The system was designed around the company's Planex laser system. It provides turnkey operation and reduces the development cycle time by providing easy integration into advanced fibre-optic sensing and monitoring systems. The unit offers ultralow phase noise and relative intensity noise, and includes ports for monitoring the optical signal, RF beat frequency and phase-locked loop lock signal. It contains two lasers with specified wavelengths, narrow linewidths of <15 kHz with long coherence lengths, polarization-maintaining output fibres, optional higher output, selectable frequency-offset locking and monitoring, and fast wavelength tunability. A graphical user interface and a USB connector provide external monitoring and control. It comes in a 2U, 19-inch rack-mount version, with an OEM version planned for the first quarter of 2012.

www.rio-inc.com

Microwave receiver is wideband

The latest microwave receiver from Micreo (Brisbane, Queensland, Australia) offers a wideband response of 2–18 GHz in two distinct bands. The unit offers both crystal video receiver and super-heterodyne receiver capabilities. The crystal video receiver mode has a gain of 19–22.5 dB (±1.25 dB ripple) in the range of 2–8 GHz, and 20–23.5 dB (±1.25 dB ripple) in the range of 8–18 GHz, with a maximum noise figure of 5.5 dB and a minimum interchannel isolation value of 60 dB. The super-heterodyne mode has a gain of 33–38 dB (±1 dB unit-to-unit tracking) and a maximum noise figure of 7.5 dB. The device is designed as a general purpose amplifier or downconverter, as well as for use with electronic front ends. It operates at a d.c. voltage of 10 V with a maximum current of 1.2 A and an operating temperature of −54 °C to 85 °C.

www.micreo.com

Transceivers offer large dynamic range

Pharad (Glen Burnie, Maryland, USA) has introduced a new series of eight high-dynamic-range RF photonic transceivers. The various models operate from as low as 3 MHz up to 40 GHz. The company says the devices offer a spurious-free dynamic range of up to 120 dB $\text{Hz}^{2/3}$ for use in high-performance RF photonic links that require large bandwidths. The multiband devices allow users to distribute many different RF signals remotely using a single transceiver. The company has designed the transceivers to be off-the-shelf products because of the growing demand for such equipment. The devices are aimed at applications such as communications, radar, electronic warfare, remote antenna distribution, aircraft and shipboard RF distribution systems, commercial wireless networks and satellite communications platforms.

www.pharad.com

Microwave photonics shines

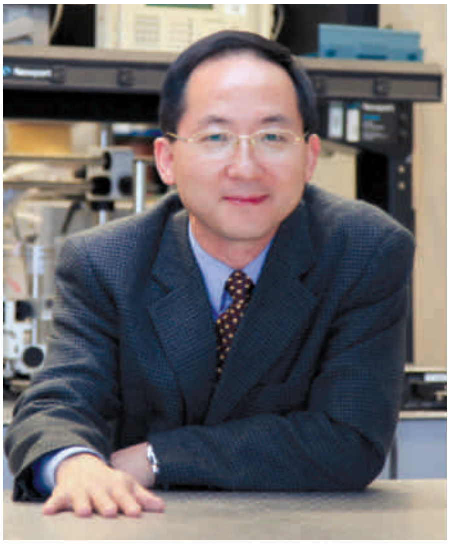
The combination of microwave photonics and optics has advanced many applications in defence, wireless communications, imaging and network infrastructure. **Rachel Won** talks to Jianping Yao from the University of Ottawa in Canada about the importance of this growing field.

What is microwave photonics?

Microwave photonics is a field that studies the interaction between microwave and optical waves for applications such as communications, radars, sensors and instrumentations. These applications require ever-increasing speed, bandwidth and dynamic range. They also need devices that are small, lightweight and low power, while exhibiting large tunability and strong immunity to electromagnetic interference. Digital electronics is the most widely used approach nowadays for these applications. Unfortunately, the speed of digital electronic is normally less than several gigahertz — a limit established primarily by the electronic sampling rate. The unique capabilities offered by photonics for processing ultrawide-bandwidth, high-frequency microwave signals make it a promising alternative for wideband microwave signal processing.

What applications drive the field?

Over the past 30 years, research activity in microwave photonics has focused on the generation, distribution, control and processing of microwave signals for defence applications. Some examples are low-phase-noise and high-frequency microwave sources, high-dynamic-range microwave photonic analog links, true-time-delay phased array antennas, frequency-tunable high-*Q* microwave filters and high-speed analog-to-digital convertors. The other driving force comes from broadband wireless access networks. Future networks will be expected to support wireless communications at data rates reaching multiple gigabits per second. Such speeds can be achieved by modulating digital data over a microwave carrier at the millimetre-wavelength band, such as the license-free 60 GHz band. The extremely low loss and broadband width of state-of-the-art optical fibres enable the distribution of 60 GHz signals with high efficiency between pico- or femtocells. Furthermore, the extremely low power consumption of an access network comprised of pico- or femtocells would making it much greener than current macrocell networks, which require high-power base stations. In addition to 60-GHz-over-fibre technology, broadband wireless access can also be achieved using ultrawide-bandwidth-over-fibre technology. This is different from 60 GHz technology in that it has the key advantages of being carrier-free and simple to implement, which greatly reduces installation costs.



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Yao: "The integration of microwave photonic components onto photonic-integrated circuits is crucial to the implementation of low-cost, advanced microwave photonics."

What are the most recent applications?

The first example is the use of microwave photonics for medical imaging. Microwave photonic solutions can be employed to generate high-quality and frequency-tunable terahertz waves by beating two optical wavelengths with a wavelength spacing that corresponds to a terahertz wave. Medical imaging with terahertz waves offers some unique advantages over other imaging modalities. First, it is not harmful to biological samples as the energy of a terahertz photon is one million times lower than that of an X-ray photon. Second, terahertz imaging provides spectroscopic information that is generally absent in optical, X-ray and nuclear magnet resonance images, as the unique rotational, vibrational and translational responses of molecules, radicals and ions is often in the terahertz frequency range. The second recent example of microwave photonics is for 'the internet of things', a relatively new term used to describe a global network infrastructure that links physical and virtual objects through the exploitation of data capture and communication capabilities. Using such a network, the information about an identifiable object can be collected, distributed wirelessly and then sent to the central office via optical fibres.

How much of microwave photonics has been commercialized?

Several companies have been established over the past few years to develop microwave photonic solutions for various applications. For example, Photonic Systems has developed microwave photonic links that operate at over 40 GHz and offer a range of bandwidths, noise figures and dynamic ranges. Pharad has developed optimized-performance radiofrequency photonic transceivers for high-dynamic-range and low-loss radio-over-fibre transport. OEwaves, a spin-off from Caltech, has developed ultralow-phase-noise microwave sources based on optoelectronic oscillators for high-frequency and high-performance applications.

How can the field be improved?

The integration of microwave photonic components in photonic-integrated circuits is crucial to the implementation of low-cost, advanced microwave photonics. Although microwave photonics has unique features not offered by state-of-the-art electronics, its applications are still limited because of high manufacturing costs. Recent activity in silicon photonics (photonic devices produced within a standard silicon foundry using standard silicon processing) to integrate both active and passive photonic devices in a silicon chip may help to realize integrated microwave photonics systems at significantly reduced cost and with greatly improved performance. Although the performance of silicon photonic devices is advancing at an ever-increasing pace, more effort is still needed to design and implement microwave photonic circuits on a chip for practical applications.

RACHEL WON

Rachel Won is a senior editor of Nature Photonics *in Tokyo, Japan.*

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