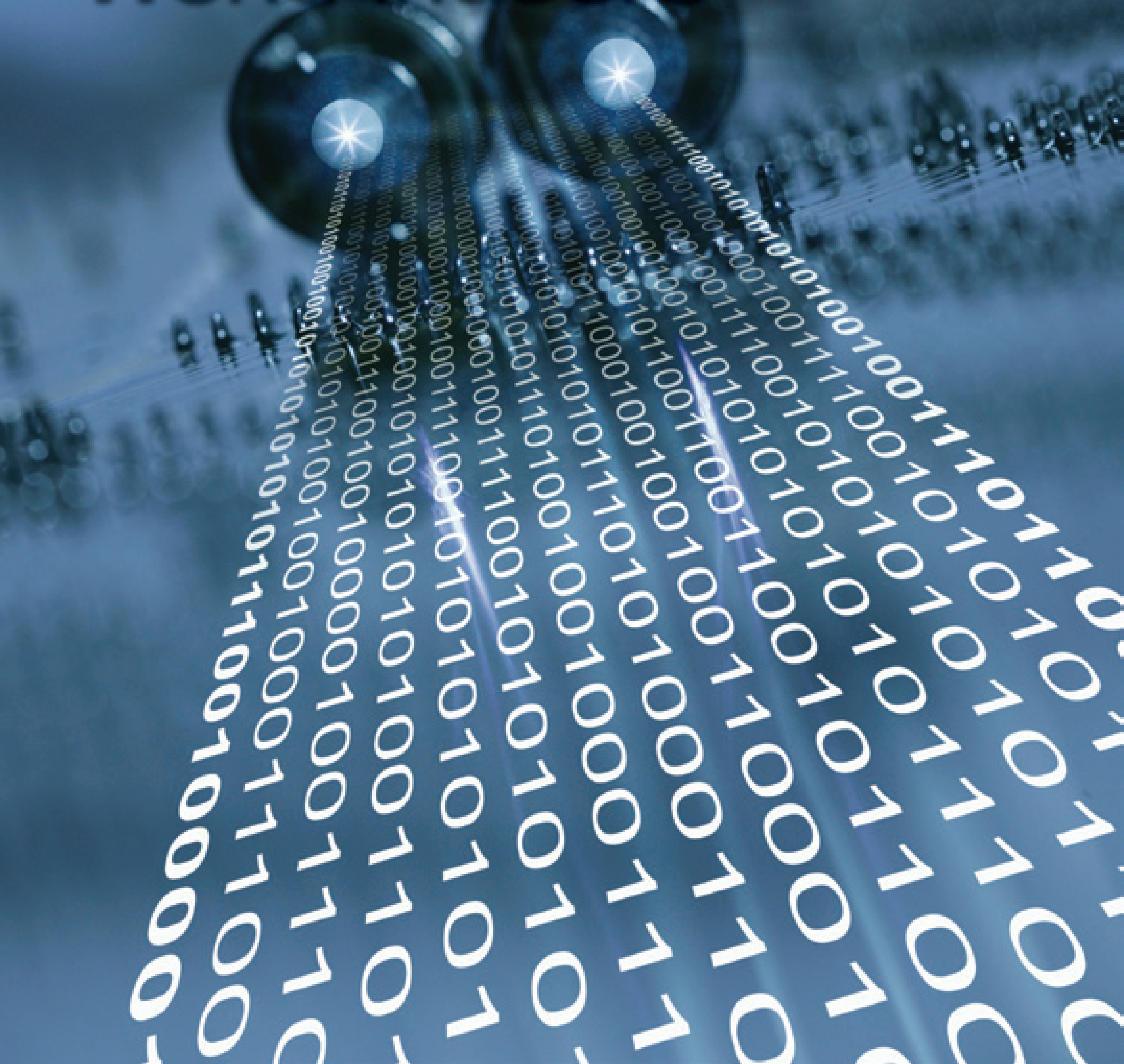
Chin-Pang Liu and Alwyn Seeds

Wireless-Over-Fiber Technology—Bringing the Wireless World Indoors



The explosive growth of the Internet would not have been possible without optical fiber, which enables the movement of enormous amounts of data over thousands of kilometers. In an increasingly important application of photonics technology, fiber is being used to transport radio frequency signals and enhance wireless coverage in buildings.

In the mid-1960s, Charles Kuen Kao first proposed long-haul and high-capacity data transmission by optical fiber. Little did he know then that his idea would transform global communications. (Kao went on to share the 2009 Nobel Prize in Physics with George Smith and Willard Boyle in recognition of his contributions to fiber optics.) In this Internet age, we can sit in the comfort of our own homes and connect instantly with other people and content from anywhere in the world, never realizing just how much distance the information must travel before reaching our computer. In addition to its use for high-capacity fixed-data-transmission systems, optical fiber is playing a key role in wireless portable and mobile communications. With the emerging 4^{th} generation cellular standard known as the long-term evolution (LTE), and the demand for ubiquitous and reliable mobile reception both indoors and out, optical fiber is increasingly being used to provide comprehensive wireless coverage within buildings.

Wireless-over-fiber basics

Wireless-over-fiber (WOF) technology refers to the transmission of wireless signals in their respective radio frequency passbands over fiber. In contrast, conventional long-haul (over 50 km) optical transmission systems carry purely digital data with occupied modulation bandwidths extending from a few MHz to the highest data rate (> 10 GHz).

Traditionally, wireless coverage inside buildings relies on the penetration of these radio frequency signals from outside base stations. However, such an indirect approach to providing in-building cellular services is highly unreliable, especially in large buildings, tunnels and basements, and therefore additional indoor antenna units must be installed. Most modern commercial office buildings already have an optical fiber infrastructure in place for carrying fixed Gigabit Ethernet traffic.

Therefore, in theory, the same optical fiber infrastructure could be shared with different cellular wireless operators for distributing cellular as well as the IEEE 802.11a/b/g/n wireless local area network (WLAN) signals. In a research project known as The Intelligent Airport (TINA), we have further investigated the feasibility of sending active radio frequency identification (RFID) tag signals in the licence-free 2.4 GHz band over optical fiber. As the project name implies, this approach could be used to create "intelligent" airports, in which the locations of air passengers and cargo could be constantly monitored through the use of active RFIDs.

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Fiber-to-the-future: Why fiber far exceeds cable

To appreciate the true value of optical fiber vs. a conventional coaxial cable, consider the following example. A standard single-mode fiber typically has an optical transmission loss of about 0.2 dB/km at a wavelength of 1,550 nm, and so a 10-km fiber will have just 2 dB of optical loss. Thus, for each dB increase in the optical transmission loss in fiber, the photodetected electrical signal power is reduced by 2 dB, because the photocurrent is linearly proportional to the optical power and the received electrical power is in turn proportional to the square of the photocurrent. A 10-km fiber is therefore equivalent to introducing a 4-dB attenuation between the input and output electrical signals.

On the other hand, a good quality coaxial cable operating at a frequency of 0.1 GHz typically shows an attenuation of 0.5 dB/m, and so a 10-km length of the same cable will attenuate the signal by a staggering 5,000 dB!

More important, the already large data transmission capacity of an optical fiber carrying a single data channel can be increased by simply adding more channels at different wavelengths—wavelength division multiplexing (WDM). For example, the TAT-14 transatlantic cable system connecting the United States, United Kingdom, France, The Netherlands, Germany and Denmark is one of many optical fiber links in the world that uses WDM. It consists of four fiber pairs; each fiber can carry 47 10-Gbit/s channels.

In other words, each fiber can carry 470 Gbits of data per second, and these numbers are expected to increase further as the system is upgraded to fit in more wavelengths and/or raise the data rate per wavelength. Such high capacities simply cannot be achieved using coaxial cables over distances exceeding a few meters. The light weight of fiber and its immunity from electromagnetic interference make it even more attractive.

Advantages of WOF

Distributing broadband wireless signals over optical fiber has a number of advantages compared with using traditional copper cabling. Because of the low transmission loss in optical fiber, the antenna units can be located where wireless coverage is required, and they are remotely connected by fiber to the base station (BS), which is centralized along with other telecom and network hardware in a common equipment room.

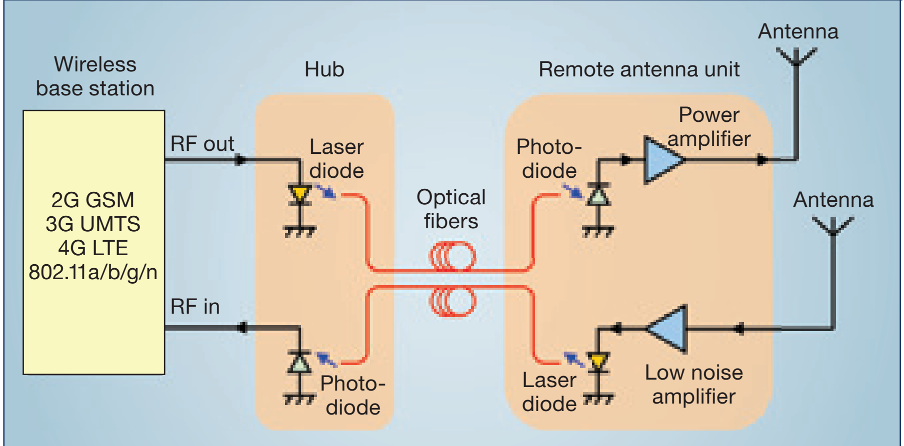
In this case, the antenna unit function can be simplified to just radio signal reception and electrical/optical conversion, and it is relatively inexpensive. WOF can also be used for any modulation format and protocol. When new standards and services are introduced, upgrades are only required for the BS hardware in the equipment room, but not the fiber infrastructure or antenna units. The wide bandwidth of optical fiber can further allow different services such as Gigabit Ethernet, IEEE 802.11a/b/g/n WLAN, GSM, 3G and 4G to share the same infrastructure, making the wireless-over-fiber approach a truly multi-operator and multi-service technology.

In a WOF scenario, the main purpose is to deliver a number of wireless services from a base station to a remote location served by an antenna unit where coverage is required. Since different wireless services use various parts of the radio spectrum, they can be combined using a frequency-selective filter. The radio frequency (RF) output of the base station is then connected to a hub where the combined RF signal directly modulates a semiconductor laser diode with a typical emission wavelength around 1,300 nm.

This direct modulation is performed by superimposing the RF signal on the laser bias current. It is the simplest technique for modulating the intensity of a laser optical output. The intensity-modulated signal is now carried by optical fiber to the designated remote antenna unit.

At the remote antenna unit, the optical signal is photodetected and further amplified before being radiated from an antenna and received by the cellular and WLAN users. This represents the down-link direction where signals are sent from the base station via fiber to the antenna unit and eventually to end users. In the up-link direction, another antenna of the remote antenna unit receives the cellular and WLAN signals from the users. These signals in turn modulate a semiconductor laser diode inside the antenna unit. After transmission over fiber, the up-link optical signal is photodetected in the hub and then fed to the base station where different cellular and WLAN signals are separated by a frequency-selective filter.

[Wireless-over-fiber system]



A typical wireless-over-fiber scenario uses separate laser diodes and photodiodes for up-link and down-link intensity modulation and photodetection.

In a practical implementation, a single hub will be connected by fibers to multiple antenna units, each serving a different sector or floor in a building so that comprehensive wireless coverage is achieved.

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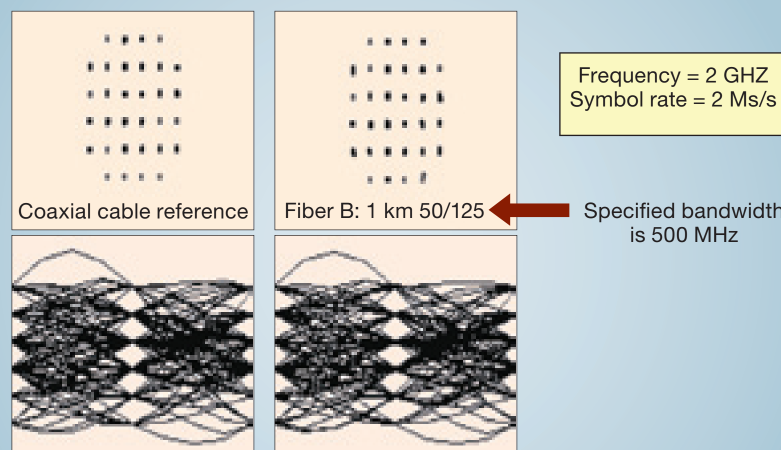
Making it work for multimode fibers

The work we have described so far, especially the long-haul high-data-rate optical transmission, implies that single-mode optical fiber is used in almost all applications. That is because, in the past, multi-mode optical fibers (MMFs) were not regarded as suitable for carrying modulated signals at microwave frequencies because they suffer from modal dispersion, limiting their bandwidth-distance products to between 500 MHz.km and 1 GHz.km at 1,300 nm wavelength.

For cellular GSM1800 and UMTS systems, this would mean a maximum fiber length of around 500 m while for IEEE 802.11a WLAN operating in the 5 GHz band, the maximum length is further reduced to less than 200 m—which is not sufficient for large in-building installations.

Commercial products for transporting cellular signals over fiber do exist. They either transmit the signal over single-mode fiber at the original radio frequency, or they transmit the signal over the MMF at a down-converted intermediate frequency, which is selected to be within the 3-dB bandwidth of the MMF. To provide in-building cellular coverage, the former method requires single-mode optical components and a dedicated fiber installation, because most installed fibers within buildings are MMF. The latter method requires complicated hardware, especially for the remote antenna units, since precise up-conversion is necessary from the IF back to the original RF.

[Constellation and eye diagram]



Constellation and eye diagram for 32-QAM transmission at 2 GHz and 2 Ms/s. (Left) The coaxial cable (reference); (Right) A 1-km multi-mode optical fiber reel B.

In 1998, Raddatz et al. showed that transmission over MMF is possible over narrow bands of frequencies beyond the 3-dB bandwidth limit of the fiber. This is because the impulse response of MMF contains a series of delta functions with different arrival times—which gives rise to high-frequency components with considerable amplitude in the frequency domain.

Our team of researchers at University College London (UCL), in collaboration with a group from the University of Cambridge, have investigated the transmission of cellular and broadband wireless IEEE 802.11b/g signals over MMF, with very promising results. In one of the experiments, we sent a digitally modulated wireless signal using 32-QAM (quadrature amplitude modulation) over an MMF. This complex digital modulation scheme requires a signal-to-noise ratio of more than 25 dB and is therefore a good test of fiber performance. A carrier frequency of 2 GHz and a symbol rate of 2 MSym/s were chosen; this corresponds to a transmission bit rate of 10 Mb/s.

The figure above shows the constellation and eye diagrams for this 32-QAM signal transmission. The left-hand side shows results for a short coaxial cable link as a reference, and the right-hand side shows results for transmission of the 2 GHz signal over a 1km MMF (50 μm core and 125 μm cladding) with a specified bandwidth of just 500 MHz. We obtained comparable results using other fiber reels. It is clear that transmission over multimode fiber at frequencies above the fiber-specified bandwidth, at least up to a length of l km, is feasible, and the performance is not significantly worse than that achieved with the short coaxial cable reference connection.

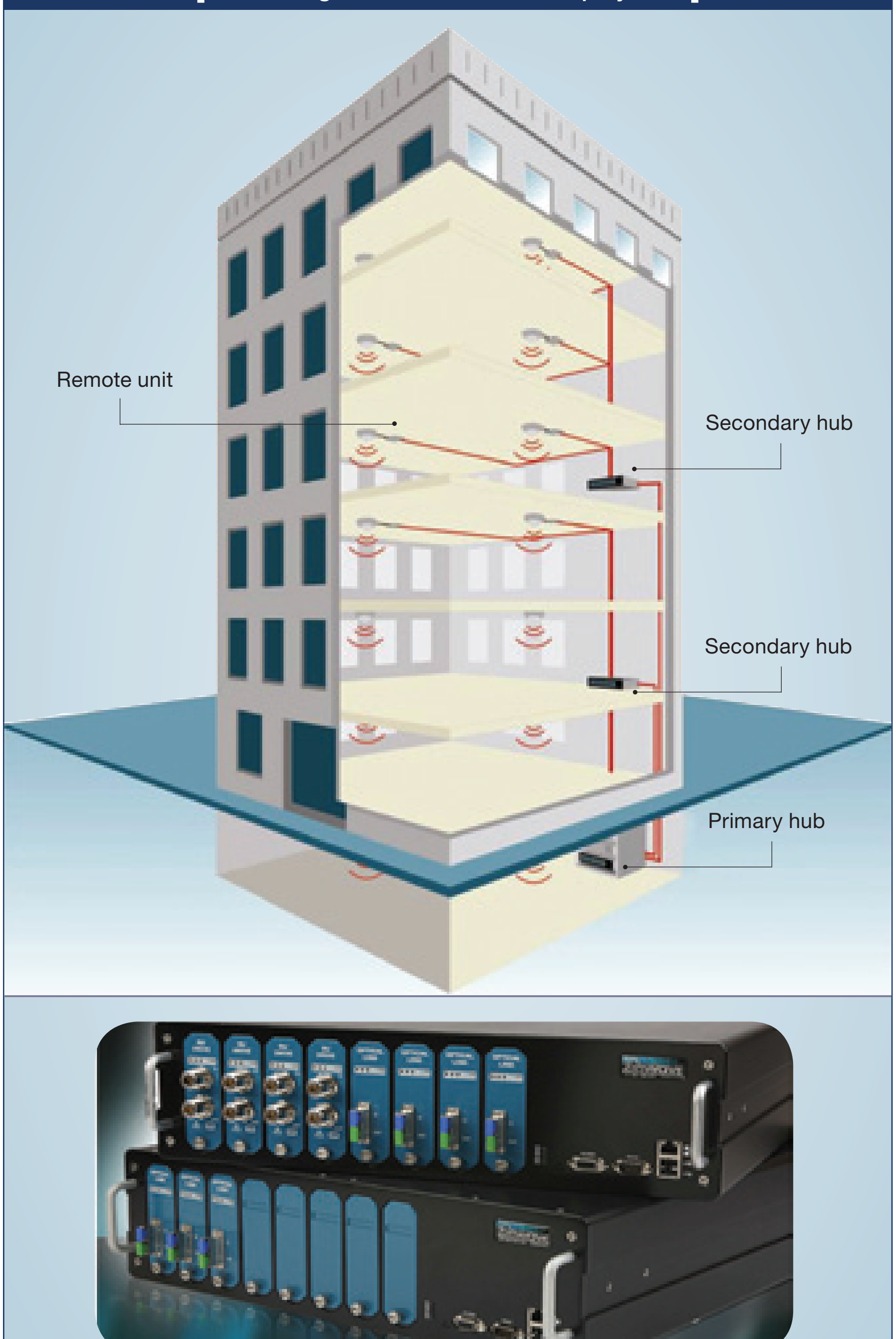
Transferring the technology to market

Based on these promising results, a company called Zinwave has been successfully spun-off from the original research led by UCL and Cambridge University. Zinwave manufactures and sells broadband wireless transmission systems using optical fiber technologies.

The figure below shows an in-building implementation scenario using the Zinwave Distributed Antenna System (DAS) and a photo of the Zinwave 3000 Hub. The Zinwave DAS can distribute a range of combined wireless services over either single-mode or multi-mode fibers.

Commercial WOF products on the market use direct modulation of laser diodes and direct photo-detection because of the technology maturity,

[In-building wireless-over-fiber deployment]



In-building wireless-over-fiber deployment for distributing multiple wireless and cellular radio services indoors (above) and commercially available Zinwave Hubs (below).

simplicity and low cost. Separate laser diodes and photodiodes are used in each remote antenna unit for electrical-to-optical and optical-to-electrical conversions, respectively. To reduce the complexity and cost of the remote antenna unit, Wake et al. proposed and demonstrated using a single waveguide type electro-absorption modulator (EAM) to perform both electrical-to-optical and optical-to-electrical conversions simultaneously.

At UCL, we have been designing and fabricating a different type of electro-absorption modulator for WOF applications. This advanced photonic device is called the asymmetric Fabry-Perot modulator (AFPM) with either an InGaAsP/InGaAsP or InGaAs/AlInGaAs multiple quantum well (MQW) electro-absorbing region and uses the quantum-confined Stark effect as the modulation mechanism. The AFPM is a reflective optical intensity modulator with a single optical window.

When the down-link optical signal is incident vertically on the AFPM within the optical window, some of the light is absorbed in the MQW region, generating a photocurrent and thus converting the modulated incident light to a down-link radio frequency signal. The residual light that has not been absorbed by the AFPM is reflected by the built-in, highly reflective distributed Bragg reflector (DBR) through the same optical window.

However, when an up-link radio frequency signal is applied to the electrical contacts of the AFPM, this reflected optical signal is also intensity-modulated by the AFPM. It can therefore be seen that the AFPM functions simultaneously as both an optical intensity modulator in the up-link direction and a photodiode in the down-link direction.

Because of the reflective nature of the AFPM, only one optical fiber is required for carrying both the down-link and up-link optical signals. Compared with the waveguide-type EAM, the AFPM also has a number of attractive features. Being a vertically addressed optical intensity modulator, the AFPM is polarization-insensitive because the electric

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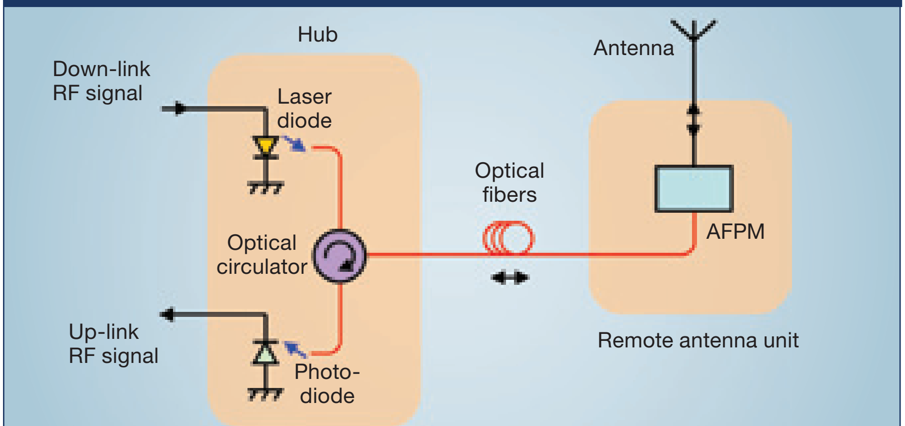
[Simplified wireless-over-fiber system]



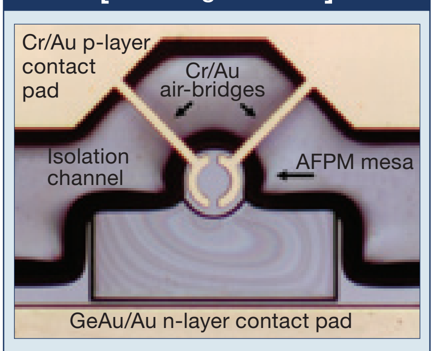
A simplified wireless-over-fiber system concept involving an AFPM at the antenna unit performing photodetection for the down-link path and optical modulation for the up-link path.

field of the input optical signal is always in the plane of the MQW layers. Thus, polarization control is not required in contrast to the waveguide type EAM.

AFPMs have been fabricated with optical window diameters of 14 μm and 20 μm using an air-bridge process, which reduces the device capacitance. As a result, 15 GHz and 22 GHz modulation bandwidths have been achieved for our AFPMs with 20 μm and 14 μm optical window sizes, respectively.

The commercial WOF products on the market typically have an upper radio frequency limit of around 6 GHz due to the small direct modulation bandwidth of commercially available semiconductor laser diodes. Also, as far as we know, most established commercial radio services for civilian and public use operate below 6 GHz, and thus the demand for bandwidth above this frequency has not been very great. However, this could change soon when more ultra-wideband products that operate between 3.1 and 10.6 GHz become available. Therefore, use of the AFPM as a single electrical/optical transducer in the remote antenna units not only reduces the active component count, but also ensures that new and emerging radio services operating at higher frequencies will also be catered to.

[Air-bridged AFPM]



Micrograph of an air-bridged AFPM with a 20-μm diameter optical window.

Optical fiber was originally invented to be a medium for long-haul high-capacity data transmission. We have shown that it is also an excellent means of distributing multiple wireless and cellular services in buildings, providing comprehensive and reliable radio coverage in otherwise hard-to-reach indoor locations without depending on signal penetration from outside base stations.

Similarly, multimode optical fiber was not previously regarded as having large enough bandwidths to carry radio frequency signals due to the modal dispersion. However, with appropriate launch techniques, multimode fiber has now been shown to be capable of carrying a range of high-frequency wireless and cellular services.

With these breakthroughs, new companies are sprouting up to manufacture a wide range of wireless-over-fiber products for the in-building wireless market. Looking ahead, with the ever growing number of wireless and cellular services operating in higher frequencies bands, new photonic devices and techniques should continuously be explored and investigated in this exciting wireless-over-fiber application. The AFPM could just be one of them. ▲

Chin-Pang Liu and Alwyn Seeds (a.seeds@ee.ucl.ac.uk) are with the department of electronic and electrical engineering, University College London, London, United Kingdom.

[References and Resources]

>> Zinwave: www.zinwave.com

>> D. Wake et al. “Passive picocell: a new concept in wireless network infrastructure,” Electron. Lett. **33**(5), 404-9 (Feb. 1997).

>> L. Raddatz et al. “High bandwidth data transmission in multimode fiber links using subcarrier multiplexing with VCSELs,” Electron. Lett. **34**, 686-8 (1998).

>> C.-P. Liu et al. “Demonstration of an Indoor Real-Time Location System with Optical Fiber Backbone,” 2009 International Topical Meeting on Microwave Photonics, Valencia, Spain, October 14-16, 2009, accepted as post-deadline paper, Fr4.1.

>> D. Wake et al. “32-QAM radio transmission over multimode fiber beyond the fiber bandwidth,” 2001 International Topical Meeting on Microwave Photonics. Post Deadline Papers. MWP’01 (Cat. No.01EX476), 2001.

>> C.P. Liu et al. “Normal-Incidence 1.56-μm MQW Asymmetric Fabry-Perot Modulator (AFPM) for Passive Picocells,” International Topical Meeting on Microwave Photonics 2002, 49-52, Awaji, Japan (Nov. 2002).

>> A. Seeds et al. “Technologies for Radio over Fiber Systems,” IEEE Photonics Society Summer Topicals 2009, Newport Beach, Calif., U.S.A., 20-22 July 2009.