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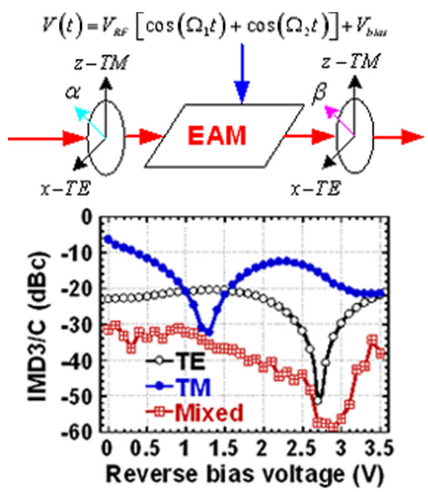
Xiupu Zhang
Bouchaib Hraimel
Ke Wu



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Breakthroughs in Optical Wireless Broadband Access Networks

Xiupu Zhang,[1] Bouchaib Hraimel,[1] and Ke Wu[2]

(Invited Paper)

[1]Advanced Photonic Systems Lab., Department of Electrical and Computer Engineering, Concordia University, Montréal, QC H3G 1M8, Canada
[2]Poly-Grames Research Centre, Department of Electrical Engineering, Center for Radiofrequency Electronics Research of Quebec, École Polytechnique de Montréal, Montréal, QC H3T 1J4, Canada

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Abstract: Enabling technologies for optical wireless broadband access networks have been explored and developed with respect to optical components, modules, transmission systems, and networks. In this paper, we review the most significant accomplishments reported during 2010 with emphasis on radio-over-fiber (RoF) technology that is critical for the deployment of optical wireless broadband access networks in the near future.

Index Terms: Microwave photonics, fiber optics systems, optical communications, integrated photonic systems.

Optical wireless broadband access networks have attracted much attention from both the academic and industrial communities, resulting in much peer-reviewed literature published during 2010, which reported innovations and accomplishments in the areas of components, modules, transmission systems, and networks. It has been known that high capacity wired access networks based on fiber-to-the-home (FTTH) technology have been successfully deployed in many countries. In the near future, optical wireless broadband access networks will be integrated into the FTTH infrastructure to cover a dedicated space or a whole metropolitan city.

Optical wireless broadband access networks can be divided into two categories in terms of radio frequency (RF) carriers: 10 GHz and less (i.e., microwaves) and millimeter-waves. For the RF carriers of 10 GHz and less, optical wireless broadband access networks are mainly used to support current wireless signal distribution, such as for second-, third, and fourth-generation, and Wi-Fi, as well as future ultra wideband (UWB) and cognitive radio systems. Optical wireless broadband access networks with millimeter-wave carriers are mainly used for the realization of high-capacity wireless signal coverage for some dedicated places and environments, such as hospitals, office buildings, and airports. Such millimeter-wave optical wireless technologies are also being considered as one of the back-haul base-station connection technologies of emerging broadband wireless services. Although millimeter-wave optical wireless platforms have been studied and developed for many years, some dedicated component, system, and networking technologies have yet to be considered mature and should be further developed so that the distribution of millimeter-wave wireless signals can be realized in a cost-effective manner. The optical wireless broadband access networks may also be used to support wireless sensor networks, including radar and imaging applications. The distribution of wireless signals through optical

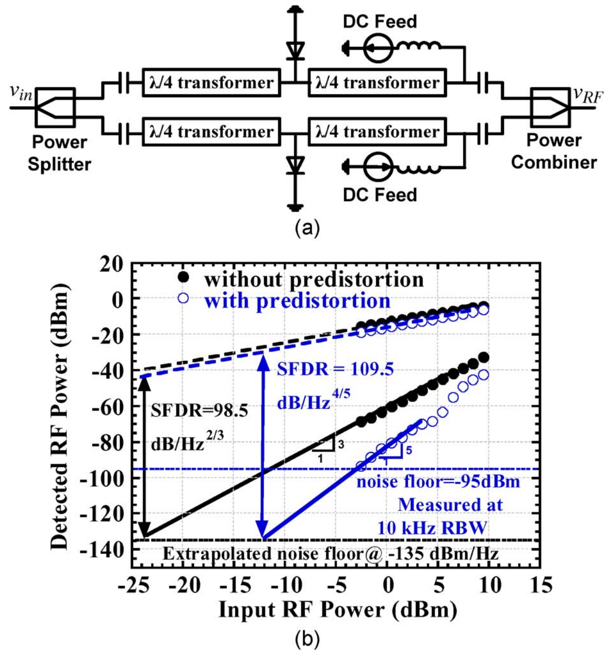

Fig. 1. (a) Predistortion circuit layout and (b) measured RF power of RF carrier and third-order intermodulation distortion (top two lines: RF carrier power; bottom two lines: third-order intermodulation nonlinear distortion power).

wireless broadband access networks can be classified into radio over fiber (RoF), intermediate frequency (IF) over fiber, and baseband over fiber or digitized RF over fiber, and among them, the RoF technology has been considered to be the most promising compared with the others. Therefore, we only highlight the accomplishments of enabling technologies related to the developments and innovations of the RoF technology during 2010.

For the breakthroughs and innovations in lasers and photonic sources that are used for the RoF systems, a feedforward linearized laser was proposed to improve modulation linearity [1]. Optically injection-locked vertical-cavity surface-emitting lasers (VCSELs) or distributed feedback (DFB) lasers were also investigated with regard to having a broad modulation bandwidth that can be used for 60-GHz millimeter-wave over fiber systems [2], [3]. Additionally, a reflective semiconductor optical amplifier (SOA) located at a base station was proposed to replace a laser for an uplink [4]. Due to limited modulation bandwidth of the reflective SOAs, this technique can be used only for uplinks with the RF carrier frequencies of less than 3 GHz. Alternatively, a saturated SOA can be used at a base station to obtain a quasi-continuous-wave light for an uplink [5]. Two lasers with orthogonally polarized lights, i.e., one for downlink and the other for uplink, are located at central stations, and thus, no lasers are required at base stations or remote antenna sites [6]. Moreover, it was found that a broadband optical source combined with a Mach–Zehnder interferometer could be used to obtain multichannel light sources for wavelength division multiplexing (WDM) RoF systems [7].

Significant accomplishments in optical modulators for optical wireless broadband access networks have been made. We have proposed a mixed-polarization linearized Mach–Zehnder modulator (MZM) that leads to a more than 10-dB improvement of spur-free dynamic range (SFDR) [8]. Later, this technique was extended to linearize a polarization-dependent electro-absorption modulator (EAM), and a $\sim$10-dB SFDR improvement was achieved [9]. Instead of using a single MZM, a dual-parallel MZM can be used to improve modulation linearity [10]. We have also proposed and investigated a low-cost predistortion circuit to linearize optical modulators [11]. Fig. 1 shows the circuit layout and measured photodetected RF power of the RF carrier and third-order intermodulation distortion after 20 km of fiber transmission with and without using such a predistortion circuit before an EAM. It was shown that an 11-dB improvement of SFDR was achieved. This circuit can also be used for the linearization of a direct-modulation laser diode, an MZM, or a phase modulator, which will fully be reported later. More importantly, such a predistortion circuit can easily be designed for the broadband operation and, thus, can be used to linearize millimeter-wave over fiber systems. An alternative technique for linearizing optical modulators and thus RoF systems was also studied, which is based on optical phase modulation in the transmitter and remodulation and optical filtering in the receiver with coherent detection [12].

For microwave photonics including RoF technology, broadband and high-power photodiodes are required. Use of two cascaded photodiodes leads to 91-GHz bandwidth and 18-dBm RF power [13], and a single photodiode was reported to generate an RF power of 29 dBm at 5 GHz [14]. A high-linearity four-photodiodes array integrated with a power combiner was demonstrated to have an RF power of 8 dBm at 20 GHz [15]. An RF power of 0.7 dBm has been achieved at 60 GHz using a single InP photodiode [16]. A broadband InP photomixer integrated with millimeter-wave antenna was fabricated and generates an RF power of 4.5 dBm at 110 GHz [17]. Instead of using a broadband photodiode for millimeter-wave over fiber systems, a omplementary metal–oxide–semiconductor (CMOS) avalanche photodiode was demonstrated to directly up-convert an IF wireless signal to 60-GHz millimeter-wave signal at base stations, where the CMOS avalanche photodiode was used for both photodetection and harmonic mixing [18].

To develop low-cost millimeter-wave broadband RoF systems, efficient and innovative interfaces between wireless and photonic signals such as optical modulators and photodetectors should be made. Novel optical modulators based on Calcium Barium Niobate materials that provide electro-optical coefficients that are roughly three times higher than $LiNBO_3$ were studied for very low-driving voltage applications [19]. In addition, a class of emerging optical modulators and photodetectors that make use of a substrate integrated waveguide (SIW) was proposed and demonstrated rather than conventional microstrip and coplanar waveguide (CPW) transverse eletromagnetic mode (TEM-mode) traveling-wave electrodes. In this way, millimeter-wave signals can be transmitted and processed with low-loss and self-packaging features with non-TEM mode propagation [20], [21].

For millimeter-wave based optical wireless broadband access networks, photonic frequency up- and down-conversion have been considered as a new low-cost technique. It was found that an EAM can be used for simultaneous frequency up- or down-conversion and optical subcarrier modulation [22], [23], resulting in a low-cost base station. The frequency down-conversion from $\sim$30 GHz to $\sim$4 GHz and optical subcarrier modulation using an EAM were validated using multiband orthogonal frequency division multiplexing (OFDM) UWB over 20 km of single-mode fiber, and an error vector magnitude (EVM) of less than -21 dB was obtained. An optical phase modulator or an MZM can also be used for the photonic generation of millimeter waves [24]–[28]. Using frequency quadrupling with an MZM, millimeter waves were optically generated with frequency hopping multiband OFDM UWB signals as optical subcarriers, and an EVM of less than -21 dB after 20 km of fiber was achieved [25]. Using frequency doubling in an optical phase modulator, a 60-GHz millimeter-wave signal was successfully distributed over 10 km of fiber, together with microwave signal at 15 GHz and baseband signal, all at 2.5 Gb/s [27]. In addition, the use of two cascaded EAMs, an SOA, or highly nonlinear fiber was investigated for the generation of millimeter-waves [29]–[31]. It was shown that two cascaded EAMs may be efficient for frequency up-conversion if the two EAMs are carefully designed, which is considered a promising technique since the two EAMs can be integrated in one chip [29]. A full-duplex 62-GHz millimeter-wave over 25-km fiber transmission system was verified, where an arrayed waveguide grating and an SOA were used for frequency up-conversion and wavelength reuse [30]. Frequency up-conversion was also obtained using four wave mixing in highly nonlinear fiber, and validated for $\sim$30 GHz millimeter-wave transmission over 25-km fiber at 2.5 Gb/s [31].

During 2010, a series of novel enabling techniques for microwave or/and millimeter-wave over fiber transmission systems have been investigated and demonstrated. We investigated optical subcarrier modulation using a low-cost EAM integrated laser for frequency hopping multiband OFDM UWB over fiber systems, showing that the system performance is limited by the EAM modulation nonlinearity induced nonlinear distortion [32], and is worse than that by the use of an MZM [33]. Therefore, maximum RF modulation power to drive an EAM is limited, resulting in low dynamic range of RoF systems. However, using the predistortion, mixed-polarization linearization, or other linearization techniques, the impact of EAM modulation nonlinearities was significantly reduced [9], [11], [12]. Transmission of millimeter-wave multiband OFDM UWB signals over fiber was also investigated using photonic frequency up- and down-conversion [22], [24], [25], as mentioned above. Transmission of both millimeter-wave wireless and baseband wired signals was validated with colorless WDM [27], [34], [35], showing that the future broadband wireless access can be incorporated into the FTTH infrastructure. A new WDM-RoF access network architecture supporting simultaneous transmission of 1.25 Gb/s wired and 63-GHz wireless signals was demonstrated using a reflective SOA [34]. Similarly, a 40-GHz millimeter-wave over 125-km fiber using four-wave mixing in an SOA for frequency up-conversion and a wired transmission, both at 2.5 Gb/s in WDM-passive optical network (PON), was demonstrated [35]. An exciting demonstration was 300 GHz wireless transmission at 12.5 Gb/s based on RoF technology [36]. For very short-reach access, wireless over multimode or plastic fiber has also been found very promising to leverage the future broadband access networks [37]–[39]. Furthermore, It was demonstrated that RoF systems support future wireless multiple-input–multiple-output (MIMO) signals [40], [41]. Simultaneous transmission of multiservice MIMO wireless signals over in-building fiber to antennas for current wireless signals was evaluated [41].

Dynamic capacity allocation algorithms must be solved for RoF systems before their commercialization. A medium-transparent medium access control (MAC) was proposed and demonstrated in 60-GHz millimeter-wave over fiber networks and can be used for RoF over bus and RoF over PON with Poisson and burst-mode traffics [42]. Moreover, integrated Ethernet PON and WiMAX over fiber was investigated [43], showing that centralized scheduling is preferred for both Ethernet PON and WiMAX. Otherwise, fiber transmission of WiMAX is limited in fiber length. WiMAX over fiber distribution was validated in a field trial for 300-km/h high-speed train systems [44], indicating that fiber length is limited by time division duplex protocol of the current WiMAX standard. Dynamics using both 1-D (optical routing) and 2-D (optical routing and electrical subcarrier multiplexing) were demonstrated for wireless over multimode fiber systems [39]. Instead of using Internet protocol (IP) layer solution for multicasting services, a dynamic wavelength router was proposed and demonstrated to support multicasting, peer-to-peer, and dynamic capacity allocation [45], [46].

References

[1] Y. Neo, S. Idrus, M. Rahmat, N. Kassim, and S. Alifah, "Laser transmitter feed-forward linearization system for radio over fiber application," in *Proc. Int. Conf. Photon.*, Langkawi, Kedah, Malaysia, Jul. 2010, pp. 1–3.

[2] A. Ng'oma, D. Fortusini, D. Parekh, W. Yang, M. Sauer, S. Benjamin, W. Hofmann, M. Amann, and C. Chang-Hasnain, "Performance of a multi-Gb/s 60 GHz radio over fiber system employing a directly modulated optically injection-locked VCSEL," *J. Lightw. Technol.*, vol. 28, no. 16, pp. 2436–2444, Aug. 2010.

[3] C. Hong, C. Zhang, M. Li, L. Zhu, L. Li, W. Hu, A. Xu, and Z. Chen, "Single-sideband modulation based on an injection-locked DFB laser in radio-over-fiber systems," *IEEE Photon. Technol. Lett.*, vol. 22, no. 7, pp. 462–464, Apr. 2010.

[4] G. de Valicourt, M. Violas, D. Wake, F. van Dijk, F. C. Ware, A. Enard, D. Maké, Z. Liu, M. Lamponi, G. Duan, and R. Brenot, "Radio-over-fiber access network architecture based on new optimized RSOA devices with large modulation bandwidth and high linearity," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 11, pp. 3248–3258, Nov. 2010.

[5] G. Puerto, J. Mora, B. Ortega, and J. Capmany, "Wavelength data rewriter for centralized-source radio over fiber access networks," *IEEE Photon. Technol. Lett.*, vol. 22, no. 15, pp. 1102–1104, Aug. 2010.

[6] F. Grassi, J. Mora, B. Ortega, and J. Capmany, "Centralized light-source optical access network based on polarization multiplexing," *Opt. Exp.*, vol. 18, no. 5, pp. 4240–4245, Mar. 2010.

[7] F. Grassi, J. Mora, B. Ortega, and J. Capmany, "Radio over fiber transceiver employing phase modulation of an optical broadband source," *Optics Express*, vol. 18, no. 21, pp. 21 750–21 756, Oct. 2010.

[8] B. Masella, B. Hraimel, and X. Zhang, "Enhanced spurious-free dynamic range using mixed polarization in optical single sideband Mach–Zehnder modulator," *J. Lightw. Technol.*, vol. 27, no. 15, pp. 3034–3041, Aug. 2009.

[9] B. Hraimel, X. Zhang, W. Jiang, K. Wu, T. Liu, T. Xu, Q. Nie, and K. Xu, "Experimental demonstration of mixed-polarization to linearize electro-absorption modulators in radio-over-fiber links," *IEEE Photon. Technol. Lett.*, vol. 23, no. 4, pp. 230–232, Feb. 2011.

[10] S. Li, X. Zheng, H. Zhang, and B. Zhou, "Highly linear radio over fiber system incorporating a single-drive dual-parallel Mach–Zehnder modulator," *IEEE Photon. Technol. Lett.*, vol. 22, no. 24, pp. 1775–1777, Dec. 2010.

[11] Y. Shen, B. Hraimel, X. Zhang, G. Cowan, K. Wu, and T. Liu, "A novel analog broadband RF predistortion circuit to linearize electro-absorption modulators in multiband OFDM radio over fiber systems," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 11, pp. 3327–3335, Nov. 2010.

[12] V. Pagan, B. Hass, and T. Murphy, "Phase modulated radio over fiber link with linearized electro-optic down-conversion," in *Proc. IEEE Topic Meeting Microw. Photon.*, Montreal, QC, Canada, 2010, pp. 189–192.
[13] J. Shi, F. Kuo, and M. Chou, "A linear cascade near ballistic uni-traveling-carrier photodiodes with extremely high saturation-current bandwidth product under a 50 ohm load," presented at the Opt. Fiber Commun. Conf., San Diego, CA, Mar. 2010, Paper PDPA6.
[14] K. Sakai, E. Ishimura, M. Nakaji, S. Itakura, Y. Hirano, and T. Aoyagi, "High-current back-illuminated partially depleted-absorber p-i-n photodiode with depleted nonabsorbing region," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 11, pp. 3154–3160, Nov. 2010.
[15] Y. Fu, H. Pan, Z. Li, and J. Campbell, "High linearity photodiode array with monolithically integrated Wilkinson power combiner," in *Proc. IEEE Topic Meeting Microw. Photon.*, Montreal, QC, Canada, 2010, pp. 111–113.
[16] Z. Li, H. Pan, Y. Fu, and J. Campbell, "Optoelectronic mixer based on high power modified uni-traveling-carrier photodiode," in *Proc. IEEE Topic Meeting Microw. Photon.*, Montreal, QC, Canada, 2010, pp. 19–21.
[17] A. Stöhr, S. Babiel, P. Cannard, B. Charbonnier, F. van Dijk, S. Fedderwitz, D. Moodie, L. Pavlovic, L. Ponnampalam, C. Renaud, D. Rogers, V. Rymanov, A. Seeds, A. Steffan, A. Umbach, and M. Weiss, "Millimeter-wave photonic components for broadband wireless systems," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 11, pp. 3071–3082, Nov. 2010.
[18] J. Kim, M. Lee, and W. Choi, "60 GHz CMOS-APD optoelectronic mixers with optimized conversion efficiency," in *Proc. IEEE Topic Meeting Microw. Photon.*, Montreal, QC, Canada, 2010, pp. 139–142.
[19] E. Mortazy, I. Stateikina, A. Tehranchi, S. Delprat, M. Chaker, and K. Wu, "Calcium Barium Niobate ridge waveguide on silicon substrate," *Opt. Eng.*, vol. 49, no. 7, pp. 074 601-1–074 601-3, Jul. 2010.
[20] E. Mortazy, X. Zhang, M. Chaker, and K. Wu, "Mode coupling between substrate integrated waveguide and coplanar waveguide for traveling-wave electro-optical modulator," *IEEE Trans. Microw. Theory Tech.*, Feb. 2011, to be published.
[21] E. Mortazy, K. Wu, and X. Zhang, "Substrate integrated waveguide traveling-wave electro-optical modulators," presented at the IEEE MTT-S Int. Microwave Symp., Workshop WFG "Emerging Optical Modulator Technologies for RF Photonics," Anaheim, CA, May 2010.
[22] B. Hraimel, X. Zhang, and K. Wu, "Photonic down conversion of millimeter-wave multiband orthogonal frequency division multiplexing ultra-wideband using four-wave mixing in an electro-absorption modulator," *J. Lightw. Technol.*, vol. 28, no. 13, pp. 1987–1993, Jul. 2010.
[23] H. Kim and J. Song, "Photonic frequency upconversion technique using electro-absorption modulator for radio-over-fiber applications," *Electron. Lett.*, vol. 46, no. 22, pp. 1512–1513, Oct. 2010.
[24] M. Mohamed, B. Hraimel, X. Zhang, M. Sakib, and K. Wu, "Frequency quadrupler for millimeter-wave multiband OFDM ultra wideband wireless signals and distribution over fiber systems," *OSA/IEEE J. Opt. Commun. Network.*, vol. 1, no. 5, pp. 428–438, Oct. 2009.
[25] M. Mohamed, X. Zhang, B. Hraimel, and K. Wu, "Optical generation of millimeter wave multiband OFDM ultra wideband wireless signal and distribution over fiber," *IEEE Photon. Technol. Lett.*, vol. 22, no. 15, pp. 1180–1182, Aug. 2010.
[26] W. Li and J. Yao, "Investigation of photonically assisted microwave frequency multiplication based on external modulation," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 11, pp. 3259–3268, Nov. 2010.
[27] H. Chien, Y. Hsueh, A. Chowdhury, J. Yu, and G. Chang, "Optical millimeter-wave generation and transmission without carrier suppression for single and multiband wireless over fiber applications," *J. Lightw. Technol.*, vol. 28, no. 16, pp. 2230–2237, Aug. 2010.
[28] J. Yu, G. Chang, Z. Jia, A. Chowdhury, M. Huang, H. Chien, Y. Huseh, W. Jian, C. Liu, and Z. Dong, "Cost-effective optical millimeter technologies and field demonstrations for very high throughput wireless over fiber access systems," *J. Lightw. Technol.*, vol. 28, no. 16, pp. 2376–2397, Aug. 2010.
[29] L. Wu, B. Hraimel, X. Zhang, M. Mohamed, C. Sui, and K. Wu, "Photonic generation of millimeter-waves using two cascaded electro-absorption modulators in radio over fiber systems," in *Proc. IEEE Topic Meeting Microw. Photon.*, Montreal, QC, Canada, 2010, pp. 298–301.
[30] H. Kim and J. Song, "Full duplex WDM based RoF system using all optical SSB frequency upconversion and wavelength reuse techniques," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 11, pp. 3175–3180, Nov. 2010.
[31] T. Wang, H. Chen, S. Xie, B. Hraimel, L. Ma, and X. Zhang, "All-optical up-conversion for 2.5-Gb/s signals in ROF systems based on FWM effect in HNLF," *Chin. Opt. Lett.*, vol. 8, no. 11, pp. 1037–1039, Nov. 2010.
[32] C. Sui, B. Hraimel, X. Zhang, L. Wu, Y. Shen, K. Wu, T. Liu, T. Xu, and Q. Nie, "Impact of electro-absorption modulator integrated laser on MB-OFDM ultra-wideband signals over fiber systems," *J. Lightw. Technol.*, vol. 28, no. 24, pp. 3548–3555, Dec. 2010.
[33] M. Sakib, B. Hraimel, X. Zhang, M. Mohamed, W. Jiang, K. Wu, and D. Shen, "Impact of optical transmission on multiband OFDM ultra-wideband wireless system with fiber distribution," *J. Lightw. Technol.*, vol. 27, no. 18, pp. 4112–4123, Sep. 2009.
[34] Y. Won, H. Kim, Y. Son, and S. Han, "Full colorless WDM radio over fiber access network supporting simultaneous transmission of millimeter-wave and baseband gigabit signals by sideband routing," *J. Lightw. Technol.*, vol. 28, no. 16, pp. 2213–2218, Aug. 2010.
[35] L. Xu, C. Chow, and H. Tsang, "Long-reach multicast high split-ratio wired and wireless WDM-PON using SOA for remote upconversion," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 11, pp. 3136–3143, Nov. 2010.
[36] H. Song, K. Ajito, A. Wakatsuki, Y. Muramoto, N. Kukutsu, Y. Kado, and T. Nagatsuma, "Terahertz wireless communication link at 300 GHz," in *Proc. IEEE Topic Meeting Microw. Photon.*, Montreal, QC, Canada, 2010, pp. 42–45.
[37] A. Seeds and T. Ismail, "Broadband access using wireless over multimode fiber systems," *J. Lightw. Technol.*, vol. 28, no. 16, pp. 2430–2435, Aug. 2010.
[38] Z. Bouhamri, Y. Le Guennec, J. Duchamp, G. Maury, A. Schimpf, V. Dobremez, L. Bidaux, and B. Cabon, "Multistandard transmission over plastic optical fiber," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 11, pp. 3109–3116, Nov. 2010.

[39] H. Yang, Y. Shi, C. Okonkwo, E. Tangdiongga, and A. Koonen, "Dynamic capacity allocation in radio over fiber links," in *Proc. IEEE Topic Meeting Microw. Photon.*, Montreal, QC, Canada, 2010, pp. 181–184.
[40] C. Liu and A. Seeds, "Transmission of wireless MIMO-type signals over a single optical fiber without WDM," *IEEE Trans. Microw. Theory Tech.*, vol. 58, no. 11, pp. 3094–3102, Nov. 2010.
[41] A. Chowdhury, H. Chien, S. Fan, J. Yu, and G. Chang, "Multi-band transport technologies for in-building host-neutral wireless over fiber access systems," *J. Lightw. Technol.*, vol. 28, no. 16, pp. 2406–2415, Aug. 2010.
[42] G. Kalfas and N. Pleros, "An agile and medium-transparent MAC protocol for 60 GHz radio over fiber local access networks," *J. Lightw. Technol.*, vol. 28, no. 16, pp. 2315–2326, Aug. 2010.
[43] B. Jung, J. Choi, Y. Han, M. Kim, and M. Kang, "Centralized scheduling mechanism for enhanced end-to-end delay and QoS support in integrated architecture of EPON and WiMAX," *J. Lightw. Technol.*, vol. 28, no. 16, pp. 2277–2288, Aug. 2010.
[44] C. Yeh, C. Chow, Y. Liu, S. Wen, S. Chen, C. Sheu, M. Tseng, J. Lin, D. Hsu, and S. Chi, "Theory and technology for standard WiMAX over fiber in high speed train systems," *J. Lightw. Technol.*, vol. 28, no. 16, pp. 2327–2336, Aug. 2010.
[45] C. Puerto, J. Mora, B. Ortega, and J. Capmany, "Selective multicast in a dynamic wavelength router for DWDM converged wired/wireless access networks," presented at the Opt. Fiber Commun. Conf., San Diego, CA, 2010, Paper OWQ3.
[46] C. Puerto, J. Mora, B. Ortega, and J. Capmany, "Strategies for P2P connectivity in reconfigurable converged wired/wireless access networks," *Opt. Exp.*, vol. 18, no. 25, pp. 26 196–26 205, Dec. 2010.