Software-defined universal microwave photonic processors

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Reconfigurable waveguide meshes are used to smoothly interface the fiber and wireless segments of information and communication technology systems.

Information and communication technology (ICT) systems are currently expanding at an awesome pace, i.e., in terms of capacity demand, number of connected end-users, and required infrastructure. According to recent forecasts, global mobile data traffic grew by 74% in 2015 alone, to reach 3.7 exabytes/month, and this figure is expected increase eight times (to reach 30.6 exabytes/month) by 2020. Furthermore, more than half of all traffic from mobile-connected devices will be offloaded to a fixed network, by means of wireless devices and femto-cells each month, and similar growth rates are predicted for global internet and data center traffic. To cope with these rapid increases, there is a need for a flexible, scalable, and future-proof solution that seamlessly interfaces the wireless and photonic segments of communication networks. In addition, emerging paradigms such as 5G communications, the Internet of Things, car-to-car communications, wireless body and personal area networks, and high-resolution sensing will put even more pressure on this requirement. In most of these scenarios, novel technology developments are needed in both the physical realm and the network architectures.

In microwave photonics (MWP) devices, the worlds of radio-frequency engineering and optoelectronics are brought together to provide an interface between the highly dissimilar media. Despite its tremendous potential, the widespread use and application of MWP is currently limited by the high-cost, bulky, complex, and power-consuming nature of its systems. Integrated microwave photonics (IMWP) have therefore been developed with the aim of incorporating MWP components/subsystems in monolithic or hybrid photonic circuits and to thus overcome some of the MWP limitations. So far, IMWP work has been focused on so-called application-specific photonic integrated circuits (ASPICs), in which a particular circuit and chip configuration are designed to perform a

Figure 1. Layouts of (a) a microwave photonics (MWP) transistor, (b) the universal MWP signal processor, and (c) the optical subsystem and module decomposition. RF: Radio frequency. AUX: Auxiliary. E/O: Electrical/optical converter. ORSE: Optical routing and switching elements. C: Software control signal. IC: Integrated circuit.

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specific MWP function. This trend, however, is leading to a considerable amount of fragmentation in the field, i.e., where the number of technological solutions is almost equal to the number of applications. As a result, the market for many of these application-specific technologies is too small to justify their further development into cost-effective industrial-volume manufacturing processes.

In our work, we have therefore developed a radically different approach in which we have designed a universal MWP signal processor that can be integrated on a chip. By programming this processor suitably, it is possible to perform all the main MWP functions. For this concept we were inspired by the flexibility of the principles employed in digital signal processor and field-programmable gate array (FPGA) electronic components, i.e., where, through a software-defined approach, common hardware is shared for multiple functionalities.

We used an MWP transistor—see Figure 1(a)—as the starting point for our approach. This device is composed of a number of subsystems—see Figure 1(c)—each of which is a collection of connected fixed-and-variable components. However, this transistor only exhibits a performance that is intermediate between an ASPIC and a universal MWP processor. This is because it does not support the reconfiguration of interconnections between its internal optical subsystems.

We therefore propose a second step in our methodology to overcome this limitation. In this second step, we use a programmable MWP processor architecture that incorporates programmable optical switching/routing elements into the MWP transistor layout. With this architecture we can thus replace the reconfigurable optical filtering systems with a more powerful and versatile optical core. A schematic diagram of this novel concept is shown in Figure 1(b), i.e., where we include optical routing and switching elements (ORSEs) after internal modulation (inside the optical core and prior to detection) to provide the interconnection reconfiguration. We find that the optical core must include both finite and infinite impulse response filters, and dispersive delay lines (which can be cascaded by an internal ORSE). Although this configuration is more versatile, it remains limited in flexibility because ad hoc subsystems must still be included and interconnected within the optical core.

The third part of our approach is the software-defined MWP processor, as illustrated in Figure 2(a). We propose the use of a photonic 2D waveguide mesh to implement the optical core of this component. We can also use software to reconfigure this same hardware so that it can also be used to support all the main functions of the device (in the same way as an FPGA operates in electronics). In our waveguide mesh network, we use tunable Mach-Zehnder interferometers (MZIs) to control the connections between waveguides. By using external electronic control signals, each MZI can be configured to operate as a directional coupler, or simply as an optical switch in a cross or bar state, to provide amplitude- and phase-controlled optical routing. This concept is illustrated in Figure 2(b), where we show with a simple example how the same hexagonal mesh can be reconfigured to implement a four-stage lattice finite impulse response filter and a four-stage ring-loaded interferometer impulse response Mach-Zehnder filter.

In summary, we have developed a new approach for realizing a universal microwave photonics signal processor. Our novel concept is based on an MWP transistor in which we incorporate a programmable MWP processor architecture for optical switching/routing. We also use a software-defined MWP processor

![Figure 2](image-url)

**Figure 2.** (a) Layout of the software-defined MWP processor. E/O and O/E (optical/electrical converter) represent the external modulator and the photodetector, respectively. Amp.: Amplifier. (b) The same 2D hexagonal waveguide mesh can be reconfigured to realize a four-stage lattice finite impulse response filter (top) and a four-stage ring-loaded interferometer impulse response Mach-Zehnder filter (bottom).

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and a reconfigurable photonic 2D waveguide mesh to realize all the main functionalities of an MWP device. In our future work we will focus on the full design of our processor within a silicon photonics platform. We aim to provide multiple functionalities within a wide (6–60GHz) spectral band, i.e., which covers most future targeted fiber-wireless ICT systems and applications.

The authors acknowledge financial support from the Research Excellency Award Program (GVA PROMETEO II/2013/012), Spanish Ministry of Economy and Competitiveness (MINECO) projects (TEC2013-42332-P PIF4ESP, TEC2015-69787-REDT PIC4TB, and TEC2014-60378-C2-1-R MEMES), as well as from FEDER (projects UPVOV 10-3E-492 and UPVOV 08-3E-008). The work of Daniel Pérez was supported by a grant from Universitat Politècnica de Valencia, through the program for training of research personnel (FPI), and the work of Ivana Gasulla was supported by MINECO through the Ramón y Cajal program.

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References