# Integrated InP Devices for Advanced Optical Modulation Formats

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***Abstract.*** *Approaches towards integration with InP technology are discussed for the development of complex optical modulator and demodulator structures for 40Gb/s and 100Gb/s transmission.*

## I. Introduction

Both the current adoption of 40 Gb/s transmission occurring in core networks, and demonstrations of 100G Ethernet transport utilise advanced modulation formats rather than simply scaling on-off key modulation from 10 Gb/s. The requirements for advanced modulation formats have provided great impetus for the development of InP-based transmitter and receiver elements, since small size and integrated functionality are increasingly valued. In the following sections, the architecture for two key modulation approaches are outlined, and the design of integrated InP devices which can enable their realisation are described.

## II. Applications Requiring Integrated Devices

### A. 40 Gb/s DQPSK

While there has been much debate over many years around the preferred modulation format for 40 Gb/s transmission, there is growing consensus that differential quadrature phase-shift key (DQPSK) [1] is the best choice for many applications. As shown in Fig. 1, DQPSK transmits 2 bits per symbol at half the clock rate of binary approaches using dual-parallel Mach-Zehnder modulators (MZMs). Both upper and lower MZMs are configured as binary phase modulators, biased at minimum optical output and driven with pre-coded NRZ data. A relative phase shift of $\pi/2$ between upper and lower branches provides quadrature addition of the 2 fields. At the receive side, a delay-and-add decoder together with a pair of balanced receivers provides binary outputs without requiring additional processing.

Key advantages of DQPSK are resilience to chromatic and polarization-mode dispersion, and reduced spectral width for compatibility with 50GHz DWDM spacing and the use of reconfigurable optical add-drop multiplexers (ROADMs). DQPSK is also advantageous compared to OOK and duobinary in terms of OSNR performance. The use of RZ pulse shaping combined with DQPSK improves the nonlinear resilience of DQPSK for long-haul transmission, and provides almost equivalent OSNR performance to binary DPSK.

Currently the main obstacle to wider deployment of 40 Gb/s DQPSK is cost. The greater complexity of DQPSK requires a larger number of components – which presently are designed to meet the demanding requirements of binary 40Gb/s DPSK – leading to high cost. However, the cost of DQPSK subsystems is soon likely to decrease below that of binary 40 Gb/s approaches. The bandwidth requirements of binary

40 Gb/s dictates the use of expensive connectorised modules for MUX, DEMUX, electrical drivers, optical transmitter and optical receivers, together with RF 'plumbing' with cable interconnects. Since DQPSK requires only bandwidths commensurate with 20 Gb/s transmission, surface-mount packaging on PCB assemblies is viable, offering significant savings over binary approaches at the full 40 GHz clock rate. A key step to realisation of this cost saving, however, is the greater integration of optoelectronic functionality discussed in following sections.

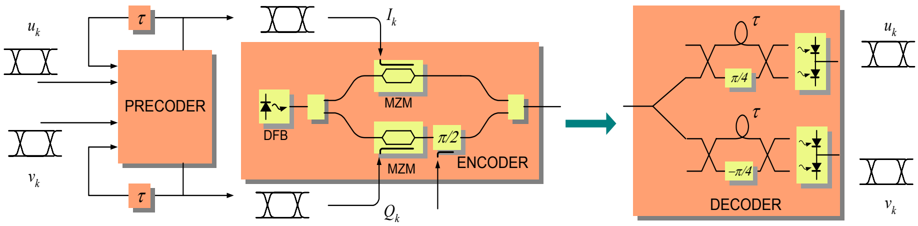


Fig. 1: Schematic illustration of optical DQPSK link.

## B. 100 Gb/s PDM-QPSK

Whereas a number of alternative approaches have been considered viable for 40 Gb/s transmission, the demands of 100 Gb/s operation has meant greater focus on a more limited number of approaches. In particular, coherent QPSK transmission employing polarization-division multiplexing (PDM) has attracted much interest. The application of post-receiver digital signal processing (DSP) has been shown to overcome many of the traditional challenges of coherent detection associated with LO stabilization and polarization management [2,3]. Since information from the transmitted optical field can be fully recovered from coherent detection with polarization diversity, post-detection DSP also allows the mitigation of chromatic dispersion accumulated over the transmission span.

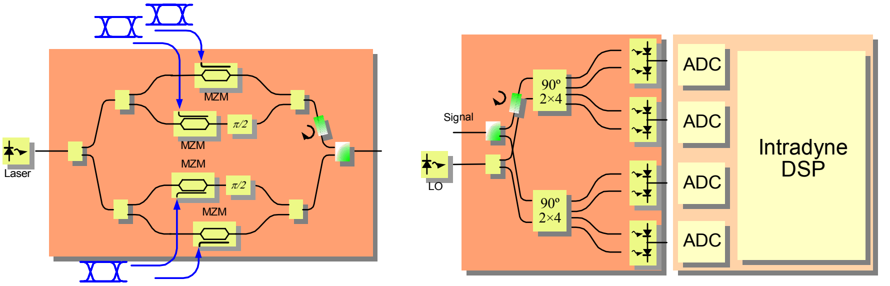


Fig. 2: Schematic illustration of PDM-QPSK link.

As shown in Fig. 2, PDM-QPSK provides 100 Gb/s capacity for a single optical carrier while operating at a 25 GHz clock rate. The 4×25 Gb/s architecture is compatible with low-cost electronic packaging, but – even more so than for DQPSK – is dependent on integration of optoelectronic functionality in order to minimize cost, footprint and assembly complexity.

## III. InP MZMs

Efficient electro-optic modulation and tight waveguide confinement allow realisation of InP dual-parallel MZ structures for QPSK modulation with very compact footprint. Figure 3 shows an RZ-QPSK layout (using a third serial MZ for RZ pulse-carving) with a chip size of 7×1 mm$^2$. The design uses proven 10 Gb/s NRZ technology, based on p-i-n epitaxy on an n+ InP substrate. The multiple quantum well (MQW) modulator core consists of InGaAsP quantum wells and Q=1.1μm InGaAsP barriers, with the guided mode highly confined to the MQW core by deep ridge etching. The RF electrodes of each MZ are independent microstrip elements, with the base of the chip grounded.

By suitably engineering the core thickness and ridge width, a lumped-element design suitable for 10 Gb/s has been modified to a travelling-wave design with impedance well-matched to 50Ω. Results in Fig. 4 for probed chip measurements illustrate $S_{11} < 10$dB and electro-optic bandwidth exceeding 20GHz, commensurate with 40 Gb/s DQPSK and 100 Gb/s PDM-QPSK operation. $V_\pi$ for InP MZMs is not a constant, but depends on the *dc* bias and operating wavelength – deeper bias reduces $V_\pi$ at the expense of additional absorption optical loss. Our design achieves < 3.5V $V_\pi$ with < 0.5dB voltage-induced absorption over C-band operation. A low value for $V_\pi$ enables full $2V_\pi$ modulation to maximise optical power and signal quality.

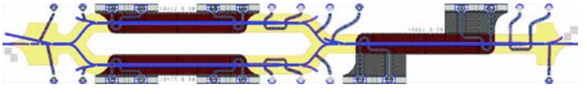

Fig. 3: Layout for integrated InP RZ-QPSK encoder chip.

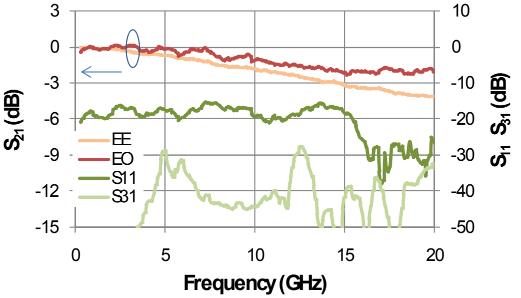


Fig. 4: Measured performance for one MZ element of a QPSK encoder chip.

The separation between upper and lower MZMs shown in Fig. 3 is a compromise between reducing RF crosstalk and minimising optical waveguide bend loss. Differential drive for each MZ is advantageous in reducing crosstalk between the multiple modulators; as shown in Fig. 4, crosstalk between MZs is < -28dB. Multiple InGaAs photodiodes are incorporated monolithically with the modulator structure, allowing monitoring of the critical optical phase shifts in individual and parallel MZMs. In conjunction with short control electrodes, monitor photodiodes enable realisation of a complete control shell for stable operation of the RZ-QPSK transmitter.

Extension of the QPSK encoder to a PDM-QPSK structure like that in Fig. 2 requires replication of the dual-parallel MZMs together with an additional input splitter. While the addition elements for polarisation rotation and multiplexing have previously been demonstrated in InP, these would require additional process development for our modulator platform. An alternative approach is to perform the polarisation manipulation functions with micro-optics. The small size of InP MZMs makes them well suited to co-packaging with the source laser, with advantages in reduced footprint, greater functionality, and eased assembly. Since our co-packaging approach already utilises micro-optics for modulator-to-fibre coupling, adding additional polarisation elements can be achieved without excessive complexity.

## IV. Integrated InP Receivers

While a number of technologies – micro-optic, fibre and PLC – have been demonstrated as viable to perform the delay-and-add functionality for DPSK systems, to date commercial products use a fibre-coupled output in conjunction with fibre-coupled receiver modules. An attractive approach to reduce size, footprint and cost is to integrate all functionality on a single InP chip, combining split, delay and 90° hybrid coupler together with waveguide photodiodes. All the individual elements required have previously been demonstrated on InP. Realisation of a 3dB MMI combiner with integrated balanced detectors was achieved more than a decade ago [4]; more recently an integrated DQPSK decoder incorporating split and delay was demonstrated [5].

Whereas some functionality – hybrid coupler with waveguide photodetection – is similar for both 40 Gb/s DQPSK and 100 Gb/s PDM-QPSK, polarisation management is different for the two approaches. For DQPSK, a key challenge is to control birefringence in order to minimize polarisation-dependent frequency shift (PDF) of the decoder free-spectral range (FSR). For PDM-QPSK, additional polarisation split and rotation elements are required, but design of 90° hybrids and photodiodes is eased, since these may operate with only TE inputs. One attractive option is to adopt micro-optics to perform the delay and polarization-management elements using co-packaging as discussed previously for PDM-QPSK transmitter.

## V. References


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