# Flexible Optical QAM Generation with a Low-Complexity Amplified InP SOA/EAM-Based Modulator

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**Abstract** *Optical quadrature amplitude modulation (QAM) is experimentally demonstrated with a low-complexity, small form-factor and lossless modulator based on a semiconductor optical amplifier and electro-absorption modulator. Flexible amplitude/phase format transmission up to 8-QAM is validated.*

## Introduction

As new telecom services are deployed and bandwidth continues to grow, high capacity is demanded for the underlying communication infrastructure. A straightforward solution that is also compatible with the migration of single transceiver modules is the use of advanced modulation with high spectral efficiency. In this framework, quadrature amplitude modulation (QAM) has been extensively investigated and is ready to enter core and metro networks thanks to the maturity of coherent optical technology.

Optical IQ-modulators for n-ary QAM have been demonstrated on InP, $LiNbO_3$ and GaAs materials with hybrid or monolithic integration. Such vector-type modulators utilize nested phase sections in interferometric Mach-Zehnder schemes in order to achieve phase/amplitude modulation.[1-3] Alternative solutions that exploit phase switching rather than phase modulation are feasible.[4-5] However, none of these devices meets the cost credentials demanded in optical access. On the contrary to core networks where a high data rate is needed, the mass market of broadband access requires a simple, non-interferometric and amplified solution with small form-factor and low electrical drive.

In this work, we show an implementation for an amplified optical QAM modulator based on a combination of semiconductor optical amplifier (SOA) and electro-absorption modulator (EAM). The performance of the multi-format transmitter is assessed in the context of optical access networks. 8-QAM transmission over 100 km is compatible with a loss budget of 34.4 dB.

## Flexible QAM Generation with SOA/EAM

The generation of QAM relies on a SOA that serves as an optical phase modulator, while the EAM modulates the intensity of the seed light injected by a seed laser. Phase modulation in the SOA is achieved by refractive index modulation through varying the actual carrier density $N$. The deviation from an equilibrium carrier density $N_0$ may stem from direct modulation of the injection current $I_{soa}$ but also from a present optical input data signal with sufficiently high modulation extinction ratio $ER$. The induced optical phase shift for a signal at the optical frequency $\nu$ for a SOA with length $L$, confinement factor $\Gamma$ and material gain $g_m$ is [6]

$$\varphi(N,\nu) = \varphi(N_0,\nu) - \frac{L}{2}\int_{N_0}^{N} \alpha(N,\nu)\frac{\partial \Gamma g_m(N,\nu)}{\partial N}\,dN$$

and the density $N$ is given by the rate equation

$$\frac{dN}{dt} = \frac{I_{soa}(\pi_P)}{eAL} - R - \frac{\Gamma g_m}{A h\nu}\left[\frac{P_{seed}}{ER}\left(1+\pi_A(ER-1)\right)\right]$$

in case of a noiseless SOA, where $\pi_P$ and $\pi_A$

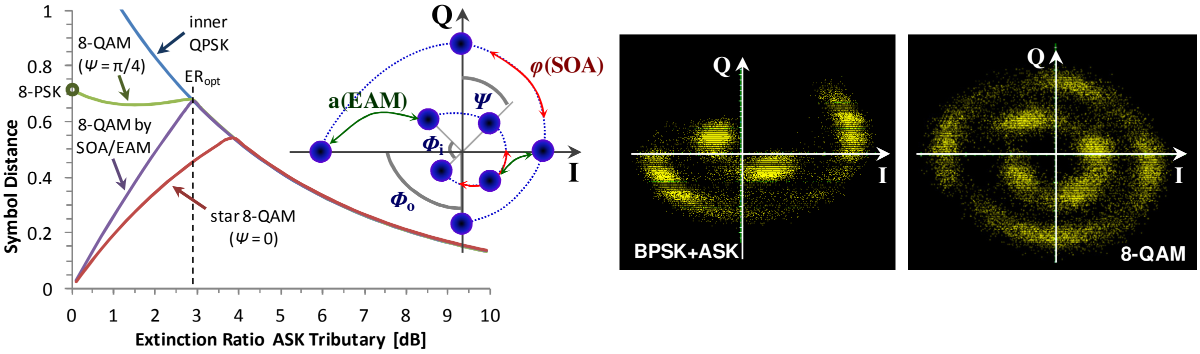

**Fig. 1:** Phasor diagram for the generation of octary QAM with a SOA/EAM, resulting in a symbol distance sensitive to the extinction of the ASK tributary, and the experimental constellations for BPSK+ASK and 8-QAM.

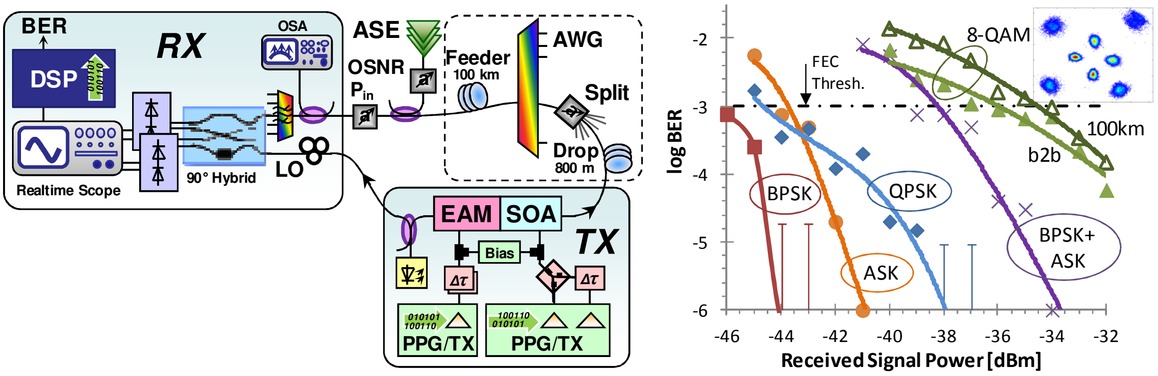

**Fig. 2:** Characterization of the flexible n-QAM transmitter. BER for ASK, BPSK, QPSK, BPSK+ASK and 8-QAM.

represent the logical data pattern for phase and amplitude modulation, respectively, the term *R* accounts for the carrier recombination, and *A* is the cross-section of the active SOA region. $P_{seed}$ denotes the optical seed power of the EAM.

Depending on the magnitude of the chirp parameter $\alpha$, a certain amount of amplitude modulation is introduced and causes the phasor of the electrical field to rotate on a spiral-shaped trajectory,[7] as sketched in Fig. 1. However, for typical chirp values good quality binary and quaternary phase modulation has been shown with low electrical drive.[7-9] A further increase of spectral efficiency for purely phase modulated signals raises scalability issues for the electrical drive of the SOA, requiring highly linear behavior to support more amplitude levels. Alternatively, a more flexible QAM transmitter with an additional EAM section provides in principle the possibility of generating arbitrary signal constellations without raising the complexity. Even in optical access, which is considered to be the most cost-sensitive segment of ICT networks, integrated SOA/EAMs are considered as the electro-optical modulator to be applied for next-generation user terminal equipment.[10]

Figure 1 shows schematically an octary QAM constellation generated by quaternary phase modulation $\varphi$ with the SOA and binary loss modulation $a$ with the EAM. Considering that the EAM provides the optical input for the subsequent SOA-based phase modulator, the angle $\Psi$ between the inner and outer constellation points will depend on the average optical power and the ER of the amplitude tributary. This provides a practical way to align the rotation between the inner and outer points. As shown in Fig. 1, this effect has significant impact on the symbol distance when comparing a star 8-QAM constellation having $\Psi = 0$ with a targeted 8-QAM at $\Psi = \pi/4$, which approaches the ideal 8-PSK for vanishing amplitude ER. The SOA/EAM with variable $\Psi$ is capable to adjust the relative rotation between inner and outer constellation points on-demand, e.g. to avoid a star-QAM. This increases the symbol distance up to a certain optimum ER, where it approaches that of an ideal QAM and is limited by the distance of the inner phase ring. The generated constellations in Fig. 1 exploit this capability of the SOA/EAM-based modulator.

## Experimental Validation

The concept of QAM generation was proven in the context of a potential low-cost user terminal transmitter in coherent ultra-dense WDM access networks.[11] Such networks can benefit from optical QAM in terms of a high sustainable per-user data rate beyond 1 Gb/s, which is provided at low capital expenditures. The SOA and EAM sections were fed with de-correlated pseudo-random bit sequences of length $2^{11}$-1, forming the quaternary and binary electrical driving signals with $110\mathrm{mA}_{pp}$ and $0.9\mathrm{V}_{pp}$, respectively. The quaternary drive for the 1.5 mm long SOA was slightly predistorted in symmetry to account for its nonlinear gain-current relation. No stabilization or feedback circuits were required as it is the case for interferometric modulators. The symbol rate was 1 Gbaud and was limited by the 1.2 GHz modulation bandwidth of the SOA. Note that high bandwidth SOAs for 10 Gbaud modulation have been demonstrated.[12] The optical seed power of the EAM was 0 dBm at 1551.2nm. The SOA/EAM had an optical bandwidth of 35nm and the loss (gain) attributed to EAM (SOA) was 8.2 (15.7) dB. The optical signal-to-noise ratio (OSNR) after the transmitter was 41 dB. The characterization setup of the flexible QAM transmitter for different amplitude and phase formats is presented in Fig. 2. Homodyne reception of the data signal was carried out exploiting the 100 kHz linewidth seed laser of the transmitter, a silicon-on-insulator 90° hybrid and a balanced photoreceiver array. The reception sensitivity was evaluated for different power and OSNR levels. A 100 GHz filter before the hybrid rejects the amplified spontaneous emission of the QAM transmitter. Demodulation was carried out using offline digital signal processing (DSP), exploiting format-specific

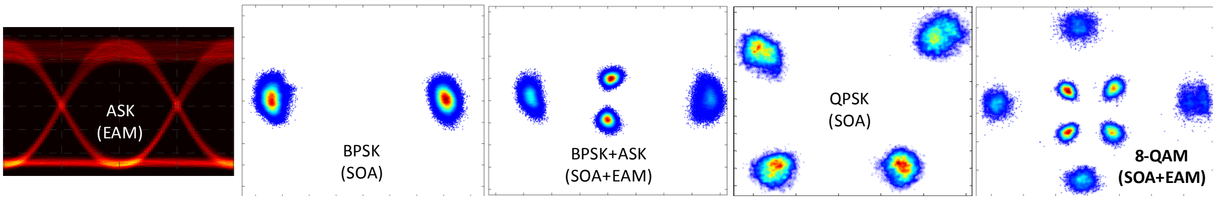

**Fig. 3:** Multi-format generation with SOA+EAM: Constellations for ASK, BPSK, BPSK+ASK, QPSK, and 8-QAM.

**Tab. 1**: Performance of the SOA/EAM transmitter.

| Modulation Format | Rate (Gb/s) | Sensitivity $P_{in}$ (dBm) | Required OSNR (dB) |
|---|---|---|---|
| ASK | 1 | -43.7 | > 9 |
| BPSK | 1 | -46.3 | > 9 |
| QPSK | 2 | -44.7 | > 9 |
| BPSK+ASK | 2 | -38.2 | > 12.8 |
| 8-QAM | 3 | -36 | > 17.8 |

carrier phase recovery schemes based on the ubiquitous Viterbi-Viterbi 4th-power method.

## Results and Discussion

The flexible QAM modulator was first assessed in its capability to generate various formats with spectral efficiencies up to 3 bits/symbol, as they are listed in Table 1. The back-to-back reception performance is presented in Fig. 2 for the given delivered OSNR. Though mixed amplitude/ phase formats such as BPSK+ASK and 8-QAM showed penalties, the Reed-Solomon (255,223) forward error correction (FEC) threshold can be clearly reached. The extra penalty for 8-QAM with respect to BPSK+ASK stems from the fact that the former is more sensitive to the ASK-dependent phase modulation index (i.e. achieved phase depth per electrical drive swing), which differed by ~4% between $\Phi_i$ and $\Phi_o$ (see Fig. 1) of the inner and outer 8-QAM rings. Multi-format reception has been verified at a degraded OSNR and a constant received signal power of -32 dBm. 8-QAM can be still received with an OSNR of 18 dB, proving viability for simultaneous operation of multiple transmitters, which would accumulate amplified spontaneous emission. Figure 4 shows the obtained constellations for several formats.

Transmission measurements over dispersion-uncompensated standard single-mode fiber were carried out due to the targeted application in long-reach coherent metro-access networks. A 100 km long feeder fiber, an arrayed waveguide grating (AWG), a variable attenuator that emulates a passive splitter, and an 800 m short drop fiber span were emulating a realistic distribution plant of a coherent access network. The ultra-dense WDM channels are thereby delivered/collected to/from the users via a passive WDM+split combination and sliced by means of coherent detection at the receiver. Transmission over 100 km can be achieved with FEC for the 3 Gb/s 8-QAM (Fig. 2). Frequency offset compensation using a novel phase-entropy algorithm has been used as standard phase-increment approaches failed to provide sufficient accuracy in the presence of significant constellation impairments.[13] There is a small penalty of 1.6 dB for 8-QAM with respect to the back-to-back characterization. The signal launch of 3 dBm leads to a compatible loss budget of 37.4 dB between QAM transmitter and coherent receiver. This confirms the feasibility of octary QAM generated by a SOA/EAM for its potential application in coherent PONs, since the budget can be eroded to support a high enough user split: A density of 640 users can be implemented via a split of 1:16 per 100-GHz WDM channel, leading together with the 100 km reach to an overall required loss budget of 36.6 dB in case of a 100 km reach. Alternatively, a 1000 user scenario with reduced 50 km reach and 1:32 split per 100-GHz WDM channel (loss budget of 29.4 dB) can also be supported.

## Conclusions

A low-complexity InP SOA/EAM-based QAM modulator has been demonstrated to generate QAM with a spectral efficiency of 3 bits/symbol. The applicability to long-reach and high capacity coherent optical access networks was validated.

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