Flexible quadrature amplitude modulation with semiconductor optical amplifier and electroabsorption modulator

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Optical quadrature amplitude modulation (QAM) is experimentally demonstrated with a low-complexity modulator based on a semiconductor optical amplifier and electroabsorption modulator. Flexible amplitude/phase format transmission is achieved. The applicability of octary QAM for coherent optical access networks with sustainable 3 Gb/s per-user bandwidth is investigated for a long reach of 100 km, and its compatibility with a potentially high split is verified.

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Triple-play has become a reality, and services such as three-dimensional television are about to inundate the networks. At its cusp of evolution, mature time division multiplexing (TDM) equipment currently penetrates fiber-to-the-home (FTTH) markets. Further capacity extension has been demonstrated by inclusion of wavelength division multiplexing (WDM) [1–3]. On the other hand, a high sustainable per-user bandwidth can be achieved through advanced modulation schemes such as orthogonal frequency division multiplexing [4]. However, these approaches do not scale well with a high guaranteed data rate and loss budget, respectively. Next-generation optical access will require a disruptive approach on how the network and the subsystems thereof are perceived. This migration will be unquestionably based on a shift from electrical TDM toward the optical WDM domain.

Coherent ultradense WDM (UDWDM) passive optical networks (PONs) are an attractive solution to provide a very high user count, together with high symmetrical per-customer bandwidth and a high compatible loss budget. The key enabling technology is the filterless optical selection of user channels by means of coherent detection, which allows a much better use of available spectrum. Recently, a potentially cost-effective UDWDMPON prototype has been demonstrated [5], showing real-time downstream reception of 0.3 Gb/s in a back-to-back loss budget of 50 dB, using electrical differential phase shift keying at a channel spacing of 2.8 GHz. What still remains open is how to introduce higher-order optical quadrature amplitude modulation (QAM) formats with low-cost off-the-shelf devices in order to provide an upgrade path toward a higher data rate and/or customer density. QAM formats such as 8-QAM have been widely adopted in long-haul networks [6]. However, they require rather complex and bulky interferometric modulators.

A possible upgrade path for multiformat QAM generationis to exploit a combination of semiconductor optical amplifier (SOA) and electroabsorption modulator (EAM) as a cost-effective, integrable, and amplified transmitter with a small form factor. In this scheme, the SOA serves as an optical phase modulator, while the EAM modulates the intensity of the seed light injected by atunable laser, which would also serve as local oscillator for the downstream reception [5]. 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 the presence of an optical input data signal. The latter depends on the amplitude modulation depth μ of the input signal, defined as the ratio between modulated and unmodulated optical power. The induced optical phase shift for a signal at the optical frequency ν for an SOA with length L, confinement factor Γ, and material gain g_m is [7]

$$\varphi(N,\nu) = \varphi(N_0,\nu) - \frac{L}{2}\int_{N_0}^{N} \alpha(N,\nu)\frac{\partial \Gamma g_m(N,\nu)}{\partial N}\mathrm{d}N, \quad (1)$$

and the carrier density is given by the rate equation

$$\frac{dN}{dt} = \frac{I_{\text{soa}}(\pi_P)}{eAL} - R - \frac{\Gamma g_m P_{\text{seed}}}{Ah\nu}[1 + \mu(\pi_{\text{A}} - 1)] \quad (2)$$

in case of a noiseless SOA, where π_P and π_A represent the logical data patterns for phase and amplitude modulation, respectively, e is the electron charge, the term R accounts for the carrier recombination, A is the cross-sectional area of the active region in the SOA, and h the Planck constant. P_{seed} denotes the optical EAM seed.

Depending on the magnitude of the chirp parameter α, a certain amount of amplitude modulation is introduced and causes the phasor of the electrical field to rotate on a spiral-shaped trajectory [8]. However, for typical values, good quality binary and quaternary phase modulation (BPSK, QPSK) have been demonstrated with high chirp values of 6.9 to 12.8, leading to a low required electrical drive [8–10]. A further increase of spectral efficiency for pure phase modulation raises scalability issues in terms of electrical driving, 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: integrated SOA/EAM devices have already entered the field of optical access [2]. Figure 1 shows schematically an octary QAM constellation generated by quaternary phase modulation φ with the SOA and binary loss modulation a with the EAM. Considering that the EAM provides the optical input for the subsequent SOA, the angle Ψ between inner and outer constellation points will depend on the average optical power and the amplitude modulation depth μ. 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 minimum symbol distance when comparing a star 8-QAM having $\Psi = 0$ with a targeted 8-QAM at $\Psi = \pi/4$, which approaches the ideal 8-PSK for vanishing μ. The SOA/EAM with variable Ψ is capable of on-demand adjustment of the relative rotation between inner and outer constellation points to avoid a star-QAM. This increases the minimum symbol distance up to a certain optimum μ, where it approaches that of an ideal QAM and is limited by the distance of the inner phase ring.

The QAM concept was proven in context of potential low-cost transmitters in optical network units (ONU) of coherent PONs. The SOA and EAM were fed with decorrelated pseudo-random bit sequences with a length of $2^{11} - 1$, 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 its symmetry to cope with its nonlinear phase-current relation. The symbol rate was 1 Gbaud for this proof of concept and limited by the 1.2 GHz modulation bandwidth of the SOA. The EAM seed was 0 dBm at 1551.2 nm. The SOA/EAM had an optical bandwidth of 35 nm. Loss and gain attributed to EAM and SOA were 8.2 and 15.7 dB, respectively. The output power of the ONU was fixed to 0 dBm, and the launched optical signal-to-noise ratio (OSNR) was 41 dB. The characterization setup of the flexible ONU transmitter is presented in Fig. 2. Homodyne reception was carried out at the optical line terminal (OLT), exploiting the 100 kHz linewidth local oscillator of the ONU, a silicon-on-insulator 90° hybrid and balanced photoreceivers. Though homodyne reception is not applicable in real scenarios, it allows us to exclude

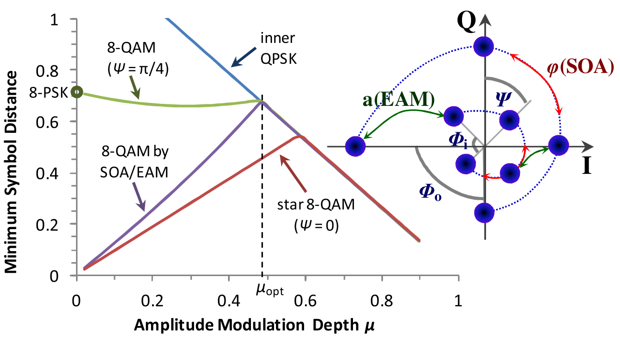

Fig. 1. (Color online) Phasor diagram for the generation of octary QAM with an SOA/EAM and resulting minimum symbol distance as function of the amplitude modulation depth.

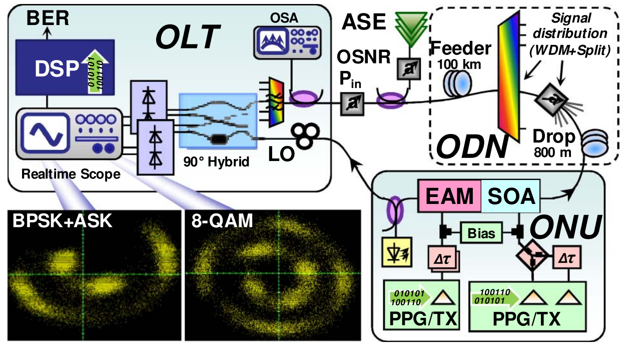

Fig. 2. (Color online) Experimental setup for the performance characterization of the m-QAM transmitter in coherent PONs.

receiver imperfections and a more accurate investigation of the transmitter. Cost-effective deployment would require an entirely integrated receiver subsystem. The reception sensitivity was evaluated for different power and OSNR levels. The latter is of practical interest, as the noise accumulation among several ONUs will degrade the delivered upstream OSNR, especially in case of high

Table 1. Performance of 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	−43.7	<9
BPSK + ASK	2	−38.2	12.8
8-QAM	3	−36	17.8

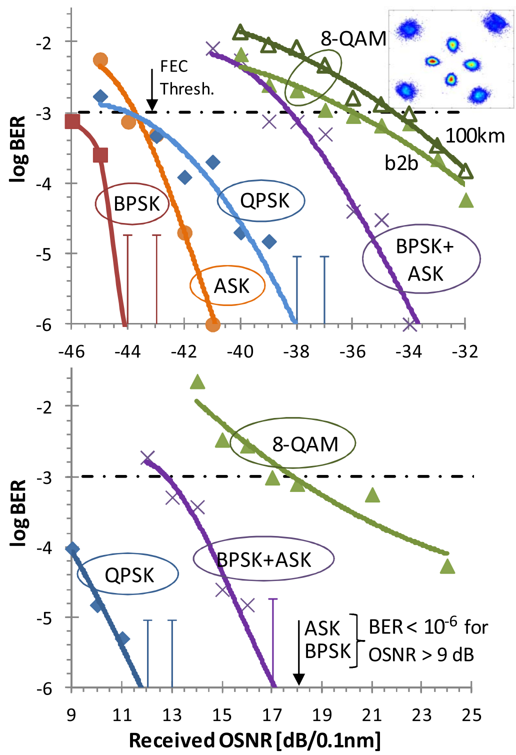

Fig. 3. (Color online) BER for ASK, BPSK, QPSK, PSK + ASK and 8-QAM as function of input power (for fixed OSNR of 41 dB for all back-to-back measurements) and as function of the delivered OSNR (for fixed input power of −32 dBm).

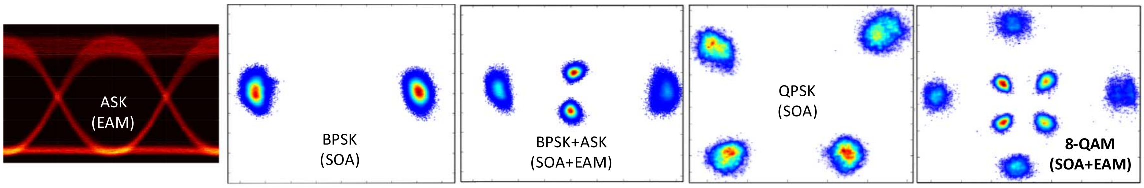

Fig. 4. (Color online) Multiformat generation with SOA + EAM: constellations for ASK, BPSK, BPSK + ASK, QPSK, 8-QAM.

user count per feeder/tree as in purely splitter-based optical distribution networks (ODNs). An optical 100 GHz filter before the hybrid accounts for a potential WDM split toward a bank of multichannel receivers. Demodulation was carried out using offline digital signal processing (DSP), exploiting format-specific carrier phase recovery schemes based on the ubiquitous Viterbi–Viterbi fourth-power method.

The flexible modulator was assessed for various formats such as amplitude shift keying (ASK), BPSK, QPSK, mixed BPSK + ASK and 8-QAM (Table 1). Figure 3 presents the back-to-back reception performance without fiber and multiplexing stages. Though the mixed BPSK + ASK and 8-QAM formats showed penalties with respect to theory [11] due to the slightly spiral-shaped constellations, the Reed–Solomon (255,223) forward error correction (FEC) threshold can be clearly reached. The extra penalty of ~3.5 dB for 8-QAM stems from the ASK-dependent phase modulation index (i.e., achieved phase depth per electrical drive swing), which differed by ~4% between Φ_i and Φ_o (see Fig. 1) of the inner and outer rings. Multiformat reception is also verified at a degraded OSNR < 18 dB, proving viability for simultaneous operation of multiple ONUs. Figure 4 shows the obtained constellations for several formats.

The applicability to coherent PONs was evaluated through transmission measurements. The passive ODN had a 100 km standard single-mode feeder fiber, a 100 GHz WDM demultiplexer, an attenuator emulating a power splitter, and an 800 m drop span. The combination of WDM and power split greatly reduces the PON budget with respect to purely power splitting ODNs. It further reduces the noise accumulation by the ONUs as fewer ultradense WDM channels are contained in a single WDM channel.

Upstream transmission can be achieved over 100 km with FEC for the 3 Gb/s 8-QAM (Fig. 1). Frequency offset compensation using a novel phase-entropy algorithm [12] has been used as standard phase-increment approaches failed to provide sufficient accuracy in the presence of significant constellation impairments. There is a small penalty of 1.6 dB for 8-QAM with respect to the back-to-back characterization. The given upstream launch leads to a compatible budget of 34.4 dB. This confirms the feasibility of the 8-QAM generated by the SOA/EAM for its potential application in coherent PONs: the obtained loss budget fits to a deployment as based on a WDM + split ODN, where each WDM channel hosts a multitude of UDWDM slots. A density of 1000 users can be implemented via a split of $1:32/\Lambda$ at a WDM spacing of $\Lambda = 100$ GHz and an extended 50 km reach, leading to an overall required budget of 29.4 dB. In case of balancing the loss between reach and split, an alternative rural scenario with a 100 km long reach and a user density of 640 users, provided via a split of $1:8/\Lambda$ and a WDM spacing of $\Lambda = 50$ GHz and resulting in a budget of 33.6 dB, can be accommodated.

In conclusion, an SOA/EAM-based modulator has been demonstrated in its capability to generate flexible QAM up to a spectral efficiency of 3 bits/symbol. The obtained performance validates the feasibility for long-reach and high capacity coherent optical access.

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