FSK+ASK/ASK Operation for Optical 20/10 Gbps Access Networks with Simple Reflective User Terminals

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Abstract: Doubling of the downstream rate by reusing the reflective upstream modulator is demonstrated. With just two photo-detectors, a RSOA and a power splitter at the ONU, a 20/10 Gbps mode can be provided per wavelength.

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1. Introduction

Fiber-to-the-Home solutions are continuously evolving and will soon demand higher data rates for the transmission of down- and upstream. Besides the use of traditional downstream detectors such as PIN or avalanche photo diodes (APD) for amplitude shift keyed (ASK) downstream signals with a data rate of 10 Gbps, upstream operation at 10 Gbps has been recently demonstrated with an RSOA-based optical network unit (ONU) [1]. The cost limitations of the components that constitute the ONU are playing an important role for a further increase of the data rates, since they prevent the use of advantageous, though more complex modulation formats that are based on phase shift keying or orthogonal frequency division multiplexing [2], [3]. While these formats are usually compromised by the required integrated delay interferometers or energy-hungry digital signal processing, FSK can be alternatively used as orthogonal modulation format with respect to ASK. However, the required optical filter that acts as FSK-to-ASK demodulator introduces wavelength-specific elements at the ONU, which is intended to be colorless for a mass deployment in a wavelength division multiplexed (WDM) access network with reduced cost. As one solution, the gain ripple of a SOA integrated with an electro-absorption modulator at the ONU can be used as comb filter [4].

In this work we propose to use the gain ripple of a RSOA as additional colorless demodulator for a FSK+ASK downstream signal. We experimentally demonstrate that the downstream data rate can be doubled to 20 Gbps, while the RSOA can be advantageously reused for 10 Gbps ASK upstream transmission.

2. Colorless FSK+ASK Operation

The design of the proposed ONU is shown together with the experimental setup for a back-to-back proof in Fig. 1. Fiber-based transmission would additionally require means of dispersion compensation, which can be integrated electronically. While the ASK downstream tributary is received with an APD, the demodulated FSK signal is detected with a PIN diode. The signal for the APD is split off with a 50/50 coupler (C_D in Fig. 1) and an isolator was placed in front of the PIN diode to avoid lasing effects from the RSOA due to back-reflections from the photo detector. The RSOA, whose gain ripple is aligned in its spectral transmission function to the incident downstream signal, as will be discussed later, performs the FSK-to-ASK conversion and is also used in half-duplex operation for upstream transmission. At the same time, the natural gain saturation of the RSOA is used to suppress the ASK component of the FSK+ASK downstream signal, which causes severe crosstalk to the FSK detection.

With this ONU design the upstream transmitter is advantageously used as FSK demodulator and provides a solution to double the downstream data rate by simply adding a second photo detector at the ONU. A second RSOA could be placed at the ONU to separate the functionalities of FSK demodulation and upstream transmission and, consequently, allow for full-duplex operation. However, half-duplex operation at twice the data rate as in [5] makes sense considering the delivery of large data contents such as for video-on-demand, where mostly downstream transmission is preferred at a given time and bandwidth partitioning will be useful.

The buried-ridge RSOA had an optical confinement of Γ~20% which ensures a low noise figure and wider optical bandwidths [6]. An anti-reflection coating was applied to the input facet of the RSOA. The gain ripple was formed via the fiber-pigtail that caused controlled reflections towards the active RSOA waveguide. The gain spectrum of the used RSOA was centered at 1561 nm and had a 3-dB small signal bandwidth of 39 nm. The gain ripple in the transmission function was 6.4 dB for a bias of 100 mA and a wavelength around 1550 nm. With a RSOA length of 700 μm a free spectral range of 0.46 nm was obtained. This transmission function suits to a comb filter with sufficient contrast for a FSK-to-ASK conversion. Due to the dependence of the refractive index on the temperature, the comb function can be tuned and in turn aligned to the downstream signal. The shift of the comb was measured with ~65 GHz/°C and was proven to be independent of the RSOA bias point in a wide temperature range (Fig. 2a).

The noise figure of the RSOA was 8.4 dB for an input of -15 dBm and a wavelength of 1550 nm. Note that the amplified spontaneous emission of the RSOA has impact on the FSK downstream detection since no optical rejection filter can be placed before the PIN diode when a colorless ONU design has to be retained.

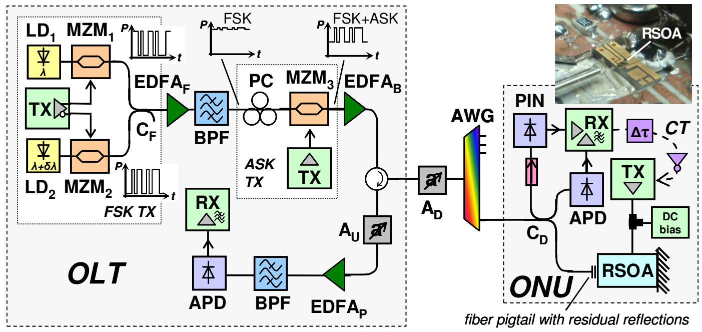

Fig. 1. Experimental proof-of-concept setup for FSK+ASK/ASK transmission.

An optical carrier at 1550.63 nm is consecutively modulated with FSK and ASK data at the optical line terminal (OLT). While the ASK modulator is comprised of a single Mach-Zehnder modulator (MZM), the FSK modulator is based on two MZMs which switch two wavelengths that are separated with a certain spacing δλ (corresponding to the frequency deviation of a FSK signal). Although this implementation of the modulator is not cost-effective and does not provide a continuous-phase FSK signal, it allows to proof the concept. No transients have been observed after combining the two wavelengths with a 50/50 coupler (C_F); the remaining intensity modulation of the FSK signal had an extinction ratio (ER) of 0.26 dB at the input of the ASK modulator, proving a constant input signal power for the ASK modulator (see inset of Fig. 2b). While the two wavelengths (λ and λ+δλ) are differentially modulated with an ER > 10 dB at the two MZMs of the FSK modulator, the ASK modulator imprints its data with a reduced ER in the range from 2 to 4 dB. Erbium-doped fiber amplifiers (EDFA) were used after the FSK- and the ASK-modulator as boosters. The output power of the second booster amplifier was fixed to 3 dBm for the FSK+ASK downstream signal and the optical signal-to-noise ratio (OSNR) after the booster was 39.9 dB. This low launch power prevents nonlinear effects in case of fiber-based WDM transmission.

An 8x8 Arrayed Waveguide Grating (AWG) was included after the OLT to account for the multiplexing device that is used as signal distributing element in WDM access networks. The OLT receiver consists of an EDFA with a noise figure of 4.7 dB as preamplifier, an optical bandpass filter with a 3-dB bandwidth of 200 GHz, and an APD.

3. Transmission Performance

Fig. 3a and 3b show the bit error ratio (BER) measurements for the downstream for the detection of the FSK and ASK tributary, respectively, at a data rate of 10 Gbps and a pseudo-random bit sequence (PRBS) of 2^{31}-1.

A figure of merit for the FSK-to-ASK conversion is the penalty that is present for the FSK detection (i.e. two present intensity modulated signals at wavelengths λ and λ+δλ) when compared with the detection of a single intensity modulated signal (at wavelength λ). This penalty has been found with 2.4 dB at a BER of 10^{-10} for the case that the second ASK carrier is placed exactly between two peaks of the comb, meaning a wavelength spacing δλ = 0.23 nm. For a smaller spacing of 0.2 and 0.17 nm the reception penalty increases by 0.3 and 2.2 dB due to the reduced suppression of the second carrier, which can be also observed in Fig. 2b.

No strong dependence on the PRBS length has been experienced. The difference in the sensitivity for the detection of an ASK signal was improved by less than 0.2 dB at a BER of 10^{-10} for a PRBS of length 2^7-1.

Pure FSK reception (Fig. 3a) without ASK modulation in the downstream is possible with a sensitivity of -17 dBm at a BER of 10^{-10} and -22.4 dBm with a Reed-Solomon (255,239) forward error correction (FEC), which allows reception at a BER level of 10^{-4}. The presence of ASK modulation at the downstream causes crosstalk for the reception of the FSK tributary and introduces penalties of 2.1 and 5 dB at the FEC level for ASK-ERs of 2 and 3 dB.

The ASK reception (Fig. 3b) is affected by the reduced ER and is compromised with the FSK reception performance. A sensitivity of -16.7 dBm is obtained at a BER of 10^{-10} for an ASK-ER of >10 dB. The penalties due to a reduced ER are 4.5 and 7.5 dB at the FEC level for ASK-ERs of 4 and 3 dB, respectively.

A possible solution to increase the ER can be the use of ASK cancellation techniques [7] at the FSK-to-ASK conversion (see '*CT*' in Fig. 1), which have been extensively proven as feed-forward approaches in many earlier works and would in principle also provide a full-duplex 10 Gbps ASK/ASK transmission mode similar as in [8]. A flexible ONU configuration can then

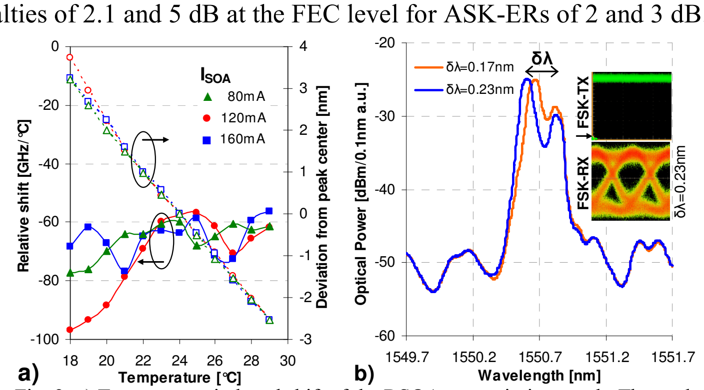

Fig. 2. a) Temperature-induced shift of the RSOA transmission comb. The peak center is defined for a temperature of 24°C. b) Spectra at the input of the FSK PIN detector for different spacing δλ. The arrow in the inset of the pure FSK downstream (FSK-TX) indicates the reference level of the detector.

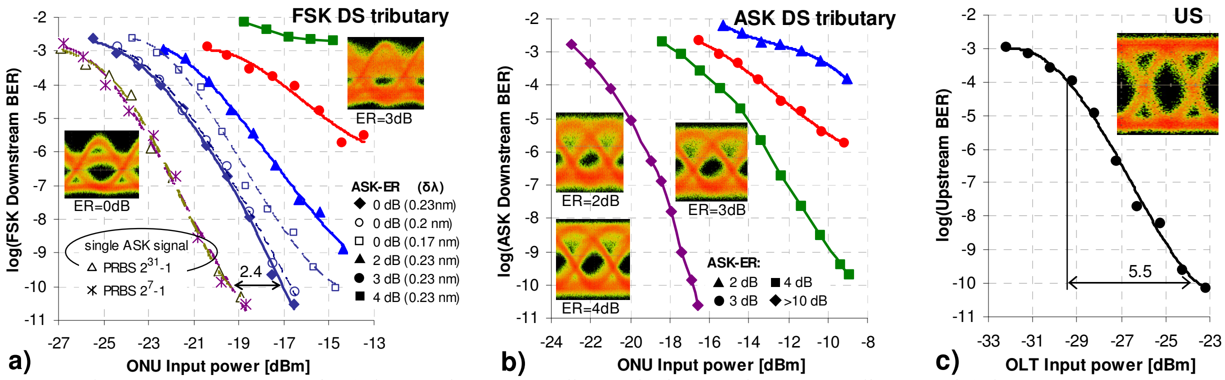

Fig. 3. BER measurements for a) the FSK downstream tributary, b) the ASK downstream tributary and c) the ASK upstream.

be obtained, allowing to switch between a full-duplex transmission with symmetrical data rate to an application-adapted high downstream data rate, without doubling the RSOA component as mentioned earlier.

The optimum ASK-ER is given by balanced BER performances for the reception of the FSK and the ASK tributaries and depends on the optical loss budget of the access network. For the given downstream launch of 3 dBm at the OLT transmitter, a budget of ~17.5 dB allows transmission at a BER level of 10^{-4} for an optimum ASK-ER of 3.5 dB, as can be seen in Fig. 4. The downstream BER limit is thereby defined as the worst BER of ASK and FSK detection. In case of a stronger FEC that allows a BER of 10^{-3} such as the RS(255,223), the budget can be increased to 20 dB for an ER of 3.7 dB. Since the upstream transmission does not limit the loss budget, as will be shown shortly, higher values for the loss budget can be obtained with a stronger downstream launch.

The input into the ONU was fixed to -15 dBm with the attenuator A_D for the upstream measurement. A BER of 10^{-3}, which is suitable for a strong FEC, can be then obtained for both, the ASK and the FSK downstream tributary. The electro-optical response of the RSOA was improved with a passive resistor-capacitor equalizer as in [1], allowing a 3-dB modulation bandwidth of 7.2 GHz for a bias of 100 mA and an optical input around -15 dBm. The bias of the RSOA was modulated with 100 mA_{pp} at a data rate of 10 Gbps and a PRBS of 2^{31}-1. An upstream ER of 6.2 dB was obtained and the OSNR after modulation with the RSOA was 31.4 dB.

A reception sensitivity of -23.7 dBm is given at a BER of 10^{-10} while another 5.5 dB of sensitivity can be gained with additional FEC (Fig. 3c). Together with the launch of -1.4 dBm from the ONU, a loss budget of 27.8 dB can be covered for the upstream transmission, showing that the downstream reception is more critical in terms of link loss.

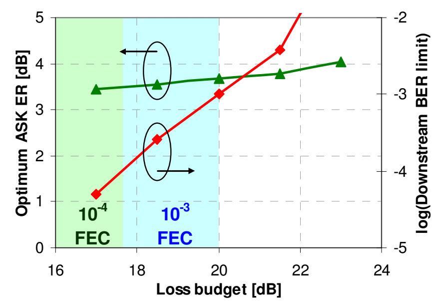

Fig. 4. Optimum ASK ER and the achieved downstream BER as function of the loss budget.

4. Conclusion

A simple and cost-effective method for colorless demodulation of a 20 Gbps FSK+ASK downstream has been presented, taking advantage of the natural gain ripple of a RSOA for the required FSK-to-ASK conversion. The comb-like transmission of the upstream modulator can be aligned in compatibility with a 100 GHz WDM grid. Loss budgets of 20 dB can be reached with FEC, while the RSOA can be reused for 10 Gbps upstream transmission.

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