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Multi-Functional SOAs in Microwave Photonic Systems

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1. Introduction

The Semiconductor Optical Amplifier (SOA) is a very attractive device for optical communication systems because of their multi-functional capability. The operation of the SOA is controlled by both the electrical and optical input signal. The SOAs have demonstrated their multi-functional capability by combining optical amplification with modulation, gating, photo-detection, dispersion compensation, linearization, etc. The chapter describes the applications of SOA-modulator, SOA-detector and SOA-dispersion compensator in microwave photonic communication systems.

The design and construction of complex optical circuits exhibiting several functionalities are difficult tasks. Optical semiconductor integrated circuits having different functional elements on a single substrate have been developed and intensively studied. In that case individual functional elements need not be connected to each other through passive waveguides. Compared to a case when functional elements are independently formed, it is simpler to apply multifunctional devices. In this case a single device replaces numerous special elements. Multi-functionality in optical communication systems decreases complexity, reduces fabrication, installation and maintenance cost, minimizes the size, enhances the reliability and allows systems to work simultaneously with suitable parameters. However, we have to compromise, because the specialised devices have better operation parameters than multi-functional devices. Therefore, the degradation of the characteristics has to be minimized; hence the study of potential multi-functional devices is a very important task.

2. Radio-over-Fibre systems

Radio-over-Fibre (RoF) technology [Seeds] offers a perspective solution to the demand for wireless connection to the costumer („last or first mile problem"). It entails the use of optical fibre links to distribute RF signals from a central location to Remote Antenna Units (RAUs). It combines the properties of the microwave and photonics approaches. In narrowband communication systems and WLANs (wireless local area networks), RF signal processing functions such as frequency up-conversion, carrier modulation, and multiplexing, are performed at the radio base station. RoF makes possible to centralise the RF signal processing functions in one shared location, and then to use optical fibre, which offers low

signal loss (0.3 dB/km for 1550 nm, and 0.5 dB/km for 1310 nm wavelengths) to distribute the RF signals to the RAUs. This way the RAUs are simplified significantly, as they only need to perform optoelectronic conversion and amplification functions. For broadband services the frequencies are in the millimetre wave range (like 60 GHz fibre radio link). Such a concept is based upon an optical link between the central station and the RAU in a picocellular structure [Ng'oma]. Some of the advantages and benefits of the RoF technology compared with electronic signal distribution are the following: low attenuation loss, large bandwidth, immunity to radio frequency interference, easy installation and maintenance, multi-operator and multi-service operation, and dynamic resource allocation. These benefits can translate into major system installation and operational savings, especially in wide-coverage broadband wireless communication systems, where a high density of RAUs is necessary.

The SOA is a potential candidate for an electro-optic transceiver (transmitter and receiver) in a RoF network. The SOA operates as a modulator to add a new channel, as a detector to drop the needed channel and as an in-line amplifier to amplify the other channels, simultaneously. It realizes a compact, small size and cost-effective radio repeater for signal distribution. Fig.1. shows a simplified system setup representing the SOA based RAU. The output power of the laser source is modulated with the 1st information channel applying a SOA-modulator. The SOA transceiver detects the 1st channel and adds the 2nd channel in the 1st stage. In the 2nd stage the SOA transceiver adds the 3rd channel, but it can detect the 1st or 2nd channel selecting by tuneable filter. Finally the receiver side every information channels can be extracted. The information channels and the bias of the SOA are separated by bias tee circuit. The separation of add and drop channels can be achieved in the electrical regime by an electrical branching filter (1st stage) or an electrical circulator with bandpass filter (2nd stage). In the first case the realisation of a reconfigurable add/drop multiplexer is difficult, in the second case an electrical filter is needed also. In the drop branch a high power RF amplifier provides the suitable power at the antenna output, and a low noise amplifier is necessary in the add branch.

Other advanced devices like electro-absorption transceiver for signal remodulation or polarization rotation remodulator have been designed though only modulation is executed, whilst with semiconductor amplifiers it's possible to perform amplification, modulation and detection with the same optical device. The signal distribution of RoF systems can be realised by point-to-point, point-to-multipoint, bus, ring and open loop topologies.
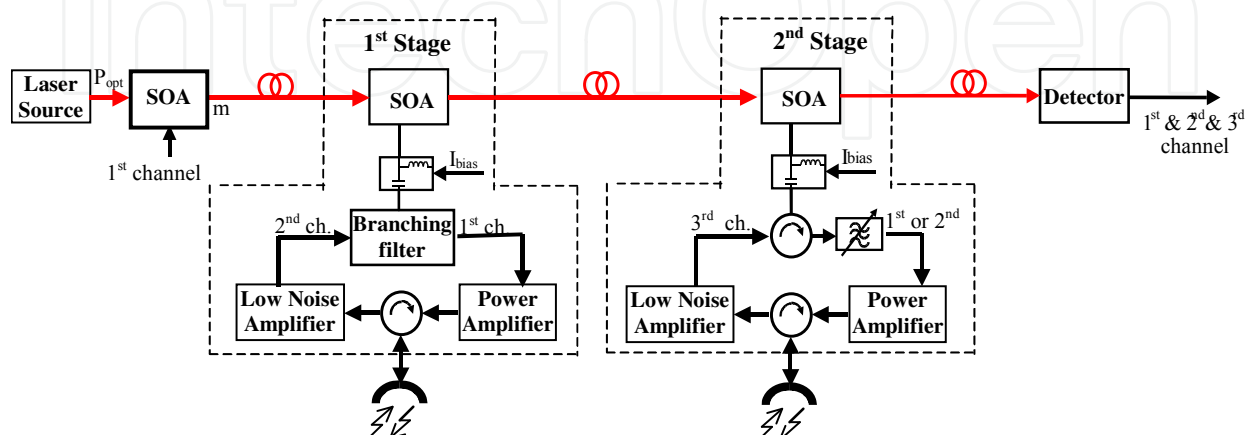

Fig. 1. Simplified system setup with SOA transceivers

2.1 Point-to-point and star topology

The Point-to-point topology is the simplest method; it is a permanent link between two endpoints. In a star topology, each RAU is connected to a central unit with a point-to-point connection. The star topology is considered the easiest topology to design and implement. Adding additional nodes is simple, but the central unit represents a single point of failure. Fig. 2. represents the star topology of RoF system. Bi-directional data transmission can be achieved over duplex optical fibre. On the other hand the uplink and downlink can be separated by optical circulator. Anyhow, the RAU consist optical source for electrical-to-optical conversion.
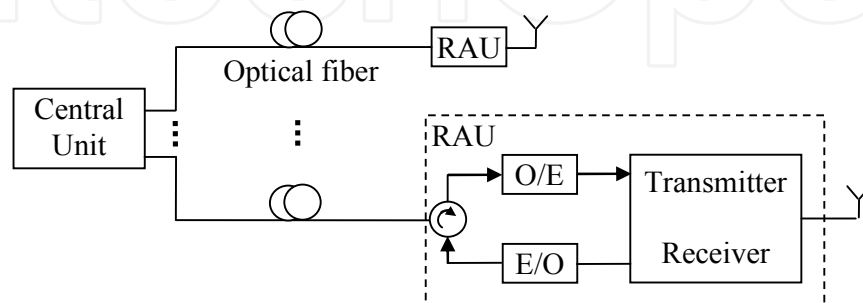

Fig. 2. Star topology, RoF system with traditional Electrical-to-Optical (E/O) and Optical-to-Electrical (O/E) converters

For more simplified RAU structure, the laser source of uplink optical carrier can be moved to the central unit and the continuous wave (CW) optical signal is transmitted over the optical fibre to the RAU. So, there are no injection of light is added at the RAU for the uplink transmission. The optical carrier is attenuated; hence some amplification should be required, in order to arrive to the maximum number of users and larger distances. Bidirectional amplification is possible by EDFAs (erbium doped fiber amplifiers) but the price is high and an additional high pump power is required. In this way, SOAs are suitable to be positioned at the simplified RAU. They not only carry out the modulation and detection but also offer an additional optical gain.
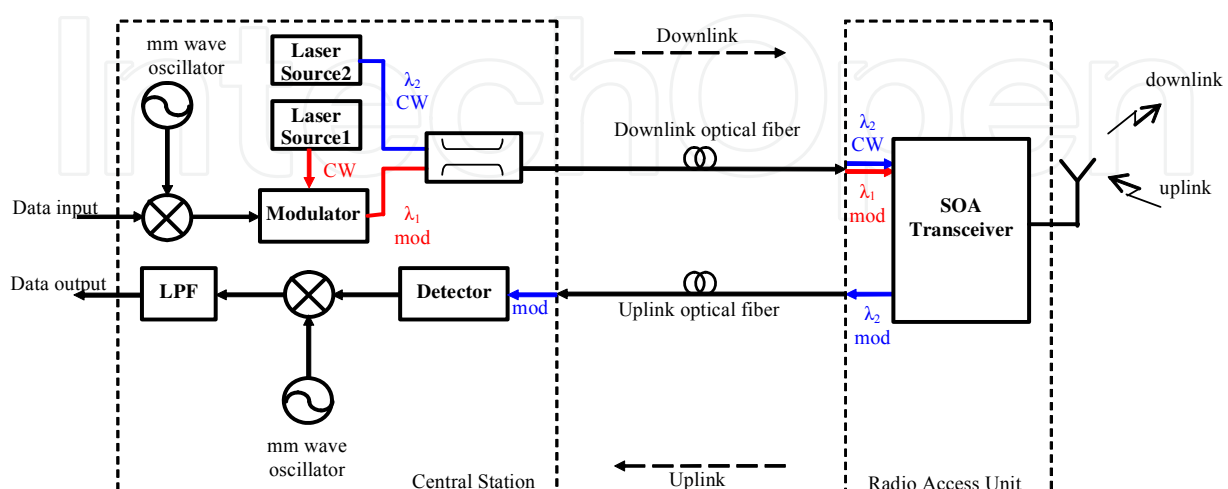

Fig. 3. Point-to-point topology RoF system applying SOA transceiver and centralised laser sources

2.2 Ring and open loop topologies

The ring topology means, that all stages are connected to one another in the shape of a closed loop, so that each stage is connected directly to two others, one on either side of it. The ring or loop network topologies are set up in a circular fashion in which data travels around the ring in one direction and each unit on the right acts as a repeater to keep the signal strong as it travels. Each stage incorporates a receiver for the incoming signal and a transmitter to send the data on to the next device in the ring. The open loop topology is not closed; it is similar to bus topology, where each node is connected to a single fibre.

Fig.4. shows a loop topology for signal distribution in a RoF system. In the network the transmission frequencies are fixed and the reception frequencies are different at each node. A control unit provides information for the nodes concerning the subcarrier frequency to be received. In the ring type version of the network a single fiber is used at each node both for transmission and reception of the information. The ring structure enables each node to communicate with any other one. In the open loop version of a network the optical fiber collects the information of the nodes and then it is routed back to make possible the reception of the collected information. Applying that folded back construction each node can communicate with any other one. However, the distance between the nodes is limited by the fiber loss and the available power.
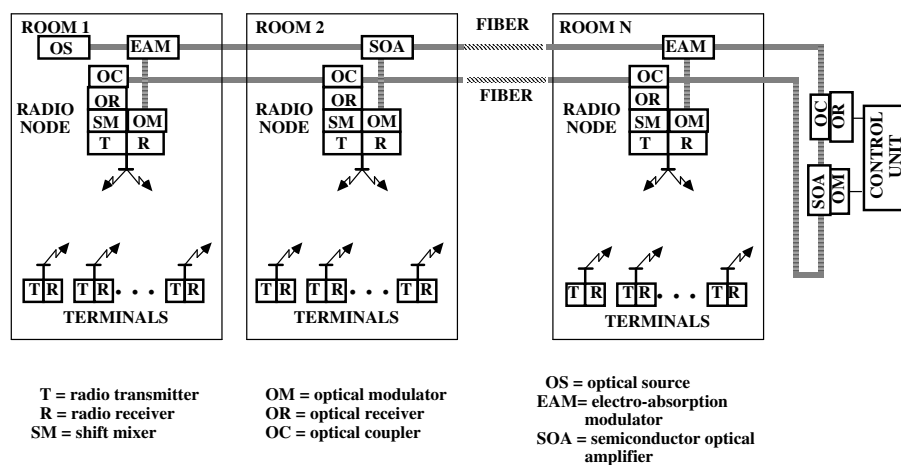

Fig. 4. Loop topology with traditional Electrical-to-Optical (E/O) and Optical-to-Electrical (O/E) converters

In Fig.5. the open loop version of a WDM-RoF network is shown. In the combined WDM-RoF network every node has a fix optical carrier instead of electrical subcarrier. In this way, the transmission capacity is extended. The multifunctional SOA can operate as a transparent unidirectional add-drop node with potential applications in photonic ring, loop or open loop networks, whose main feature is the possibility of adding new nodes and/or increasing the bit-rate for the required nodes without reconfiguring the whole network. The concept of the complete system is based on the cascaded SOA chain approach which produces simultaneous modulation and amplification. Furthermore, such read-write nodes need a minimum amount of external electronics, therefore reducing network cost and complexity. The Optical Add Drop Multiplexers (OADMs) select the dedicated optical carriers for the transceivers. The multifunctional SOA detects the information from the downlink optical carrier and modulates the uplink optical carrier with the information received from the antenna.
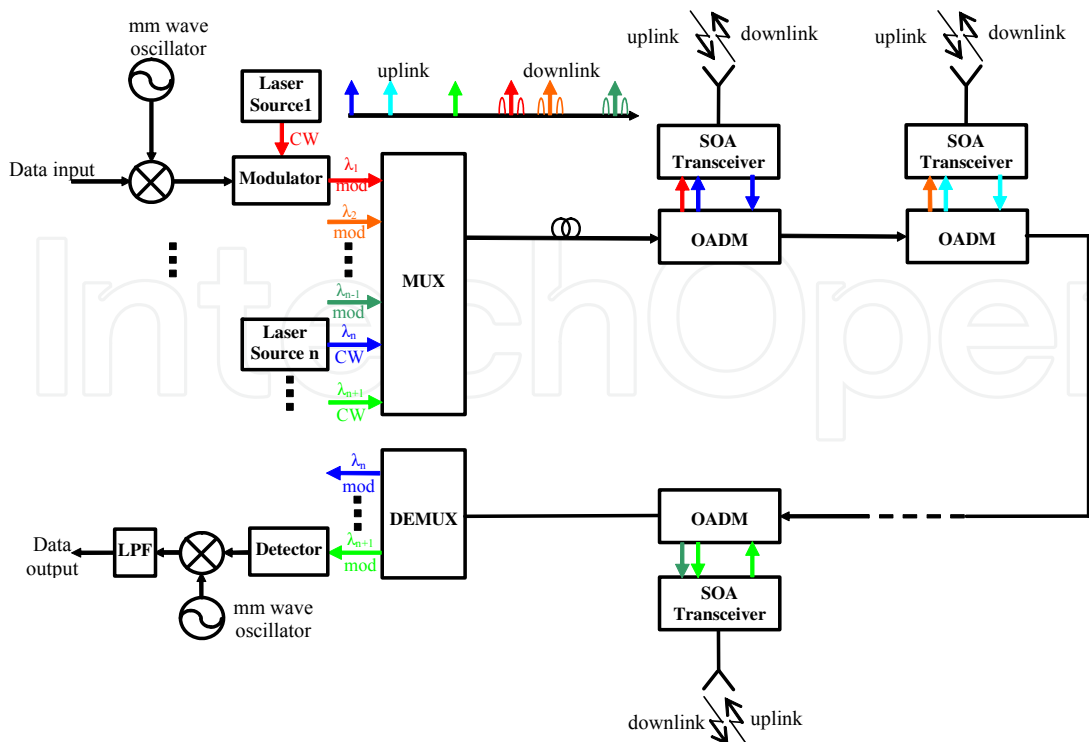
Fig. 5. WDM - RoF open loop concept with SOA transceivers

2.3 Hybrid WDM/SCM passive optical network

Fiber-to-the-home (FTTH) technology is one of the main research objectives in the "broad-band for all" concept that encourages the development of optical access infrastructure. In order to fulfil this concept, cost effective solutions must be developed to be able to offer future-proof broad-band connections to end users at a reasonable cost [Arellano]. A key element in access networks is the optical network unit (ONU) of the customer premises equipment, having a direct impact on the cost per customer, whereas, the access part represents the main segment of the total capital cost; thus, simple ONUs need to be designed. Other key desirable characteristics of an access network are the use of one single fiber for both upstream and downstream transmission in order to reduce network size and connection complexity of the outside plant [Prat], the elimination of the laser source at the ONU, thus avoiding its stabilization and provisioning, and, if possible, all ONUs being wavelength independent, to fit in a transparent wavelength-division-multiplexing scenario of a future FTTH (fiber-to-the-home) network. The SOA-modulator-detector may be used in a basic bidirectional single-fiber single-wavelength scenario for a FTTH network. However it works as a point-to-point connection, hence a reflective structure (RSOA) is more powerful.

The present passive optical network (PON) is standardised. The future, upgraded systems are waiting for standardisation. Wavelength division multiplexed-passive optical network (WDM-PON) is a promising solution for the future high-speed access networks such as FTTH or fiber to the office (FTTO) by reasons of large capacity, network security, protocol transparency and upgradability [Kang]. However, because of relatively expensive WDM components, the WDM-PON has been considered as a next-generation. Recently, to overcome this problem, there have been several proposals. Normally, two wavelength

sources are required for both up- and down-link transmission. But, one approach is re-modulation of down stream signal at ONU for upstream transmission.

The downstream signal modulates directly a laser diode, in upstream transmission the downstream signal re-modulates the optical carrier using a SOA with the SubCarrier Multiplexed (SCM) technique. No additional high cost devices are required such as external modulator and optical amplifier. A WDM-PON employing a SOA as a modulator has some advantages. The SOA gives additional gain for incident optical power to overcome device and transmission losses. Hence the SOA may be used as a modulator which accomplishes both modulation and amplification (Fig.6.). The SOA which operated in gain saturation region can reduce the intensity noise of optical signal. Due to the mixture of WDM and SCM techniques, a simple ONU which shares the same wavelength both up- and down-link transmission is possible [Kang].
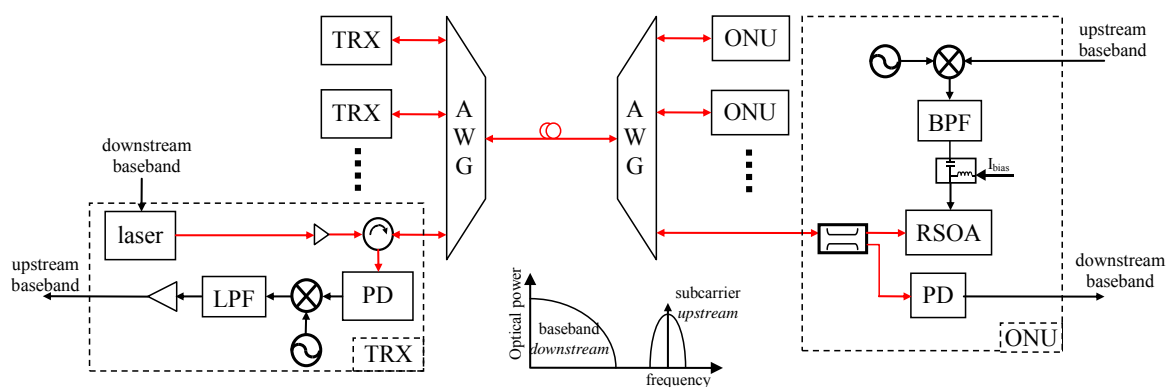

Fig. 6. Hybrid WDM/SCM PON with multifunctional SOA

3. Multi-functionality

The investigation of potential multifunctional devices is very important task for the realisation study of the proposed system concepts. Multifunctional facilities of SOAs are presented by combining optical amplification with modulation and photo-detection.

3.1 Amplification

There are several applications of SOAs in today and the future analogue and digital optical networks. The optical losses are compensated by optical amplifiers (OAs), it is well used in loss limited systems as post, in-line or pre-amplifier. The SOA is a semiconductor based, small size, compact, low cost, current driven device, which amplifies the incoming optical signal directly in the optical regime, without any optical/electrical conversion. Moreover, the semiconductor technology offers a wide flexibility in the choice of the gain peak wavelength by just appropriately choosing the material composition of the active layer. Another key advantage is that these devices can be integrated with other active or passive optical components to generate more complex functionalities. Finally, they are potentially cheap, thanks to the mature technology basis.

3.2 Detection function

The detection means optical to electrical conversion. The optical detector is characterized by the responsivity, the sensitivity and frequency response. The SOA-detector responsivity can

be determined from the variation in the injection current. The magnitude and purity of the detected signal depend on the modulation signal, the bias current, the input power and the operation parameters of the SOA [Udvary1].

3.2.1 Operation principles

Two different mechanisms induce detection in the SOA. Operated at an injection current corresponding to an electron density below transparency, the device works as a photo-detector and the detection signal arises due to absorption of the injected light and the creation of electron-hole pairs. However at injection current above transparency, that is the amplifying regime, the injected optical signal will cause stimulated transitions, which will reduce the carrier density in the gain medium. Due to these two different mechanisms of interaction, the detected electrical signal will change polarity at transparency (Fig.7.).
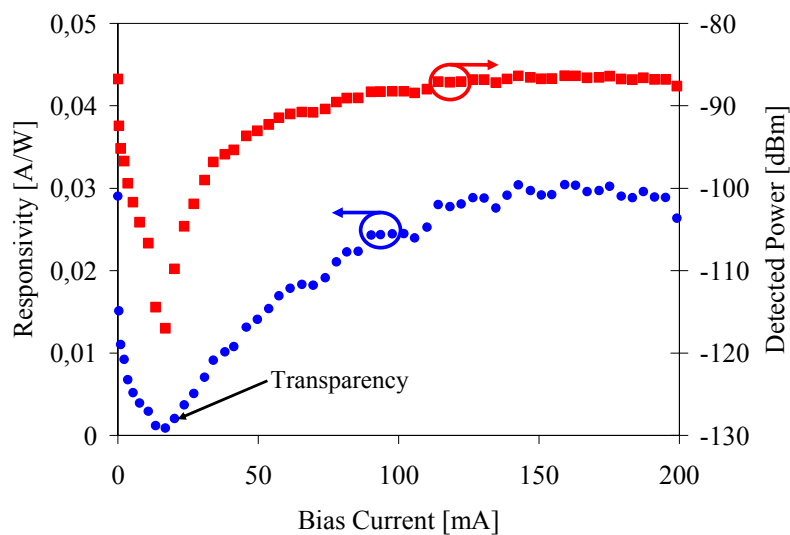

Fig. 7. Detection behaviour of SOA. Measured detected power and detection responsivity versus operation point of the SOA, optical wavelength=1550nm, Optical power at the input of the SOA-detector=40μW, Modulation depth=20%, Temperature=20°C

3.2.2 Static characteristics

The static photo-detection current is not given data in data sheets of traditionally used SOAs. In unsaturated regime this curve can be approximate calculated from the optical gain (proportional with G-1) and the input optical power (proportional with Pin). However in several cases it can only be determined by measurements.

Fig.8a depicts the electrical current as a function of the input optical power of SOA-detector. The relationship between the input optical power and the output electrical current is given by the detector responsivity, it can be determined from this curve. However this static photo-detection current is operation point and temperature sensitive. Fig.8b represents the shape of the calculated curve (based on optical gain-bias current curve), that follows the measured data.
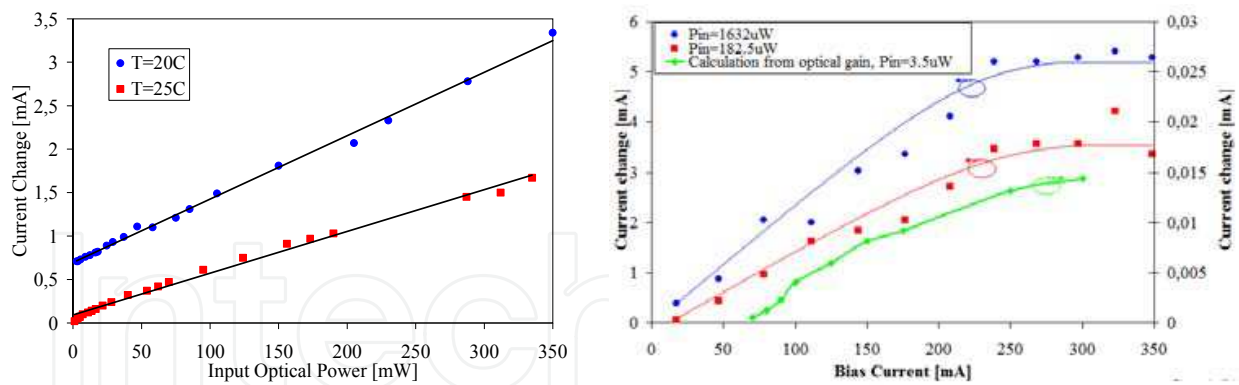
Fig. 8. Static detection characteristics of SOA-detector
Optical wavelength=1550nm, Applying isolators to eliminate the optical reflection effect
(a) Measured current change versus average optical power, at different temperatures, Bias Current=150mA
(b) Current change versus SOA operation point for different input optical power, Comparison of measurement and calculation results, Temperature=20°C

3.2.3 Detection of intensity modulated signal

The detection functionality is studied using the following link (Fig.9.). The optical signal is intensity modulated. The simplified small signal calculation applies sinusoidal modulation part. The optical link attenuates the optical signal and the SOA-detector receives it. The modulation information appears at the electrical connection of the SOA-detector.
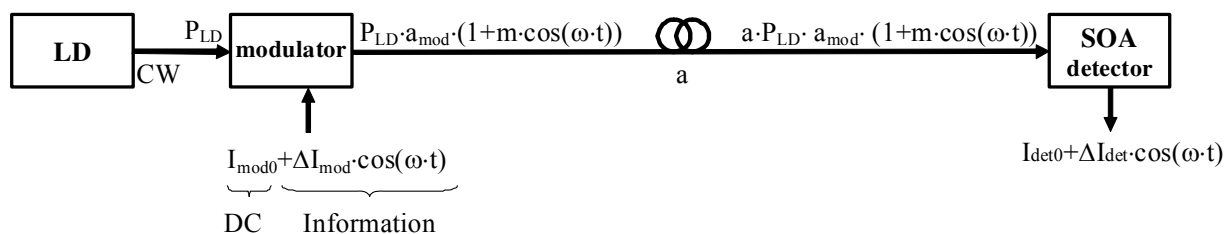

Fig. 9. Simplified block diagram for calculation of SOA-detector parameters

The detection functionality was validated by experimental work. During the measurements the SOA-detector under test was driven by the bias (dc) current and a bias tee separated the detected sinusoidal modulation signal. The polarization state of the incoming optical power was optimized by a polarization controller because the measured SOAs were polarization sensitive. The harmful effect of the optical reflection was eliminated by optical isolators. The required optical power and wavelength were produced by a tunable laser source. The intensity modulated optical signal was generated by a Mach-Zehnder modulator (MZM). The setup was controlled by a computer program, hence the measurement parameters were carefully set by the program and the measurement results were processed and restored. The detected electrical power was measured with different parameters.

When the bias current increases, i.e. the population inversion and the gain are higher the detected power increases (Fig.10). The diagram follows the shape of the optical gain curve. So the optimum bias current is the same from the viewpoint of the detection and amplification functions. The two curves have reference to two different modulation depths

of the incoming intensity modulated signal. The detected current is directly proportional to the modulation depth. Thus, the difference between the two electrical powers is about 14dB.
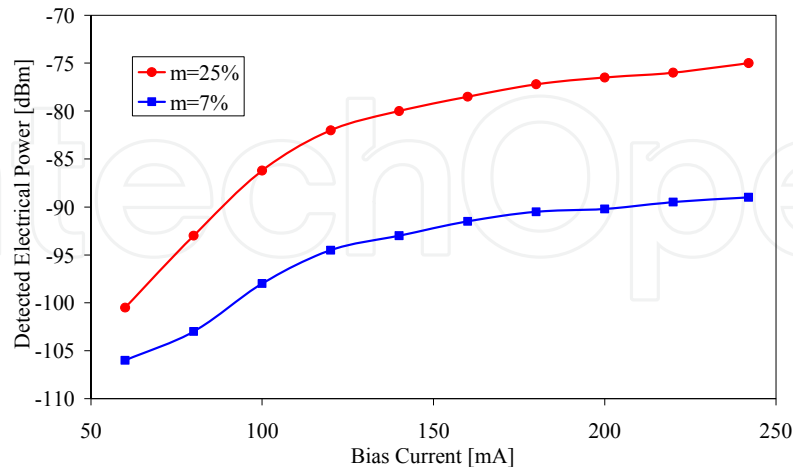

Fig. 10. Measured detected electrical power versus operation point of SOA-detector with different modulation depths, Optical power at the detector input=5µW, Modulation frequency=3GHz, Optical wavelength=1550nm, Temperature=20˚C, Applying isolators to eliminate the optical reflection effect

The result of the detection experiments over input optical power and temperature are depicted in Fig.11. In the unsaturated regime the detected electrical signal is square proportional to the optical power, but in the saturation regime the relation goes to linear proportionality. The detection is also temperature sensitive, because the operation of semiconductor devices depends on the temperature. The measurement results show, that the detection efficiency decreases, when the temperature increases.
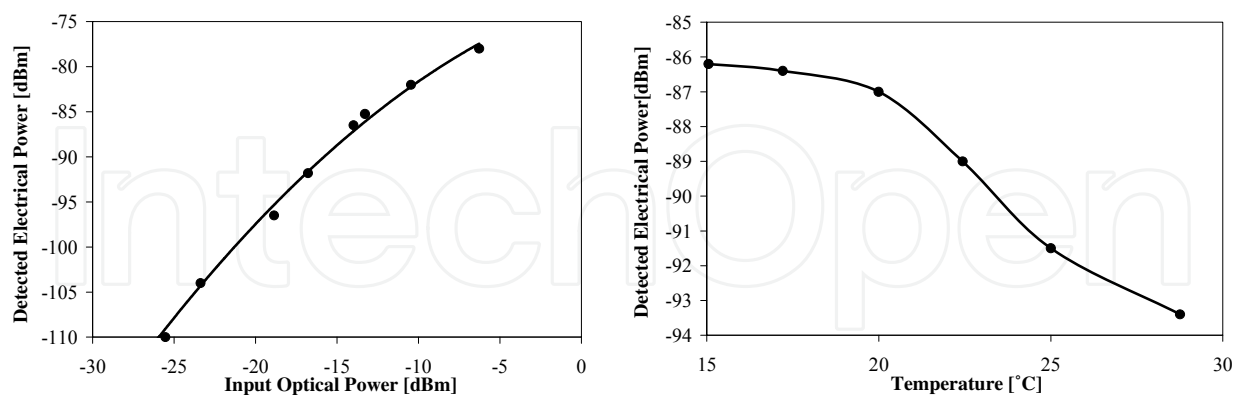

Fig. 11. Measured detected electrical power versus average input optical power (a) and temperature (b). Optical wavelength=1550nm, Bias current=200mA, Modulation frequency=3GHz, Modulation depth=25%, Isolators

3.2.4 Responsivity extraction from the measurements
The responsivity of the SOA-detector can be calculated from the measurement. If the input signal is intensity modulated, the fluctuation in the optical intensity due to modulation will

induce fluctuation in the injection current. We shall consider sinusoidal intensity modulated input optical signal

$$P_{in}(t) = a \cdot a_{mod} \cdot P_{LD} \cdot (1 + m \cdot cos\,\omega t) = P_{DC} + \Delta P_{SOA\_in}^{opt} \qquad (1)$$

where P_{in} is the input optical power of SOA-detector, P_{LD} is the average optical power of the laser, a_{mod} is the optical loss of the modulator, a is the optical loss between the modulator and SOA-detector, m is the modulation depth and ω is the angular modulation frequency. Hence the detected electrical current has cosine type component

$$I_{det\,SOA} = I_{DC} + \Delta I_{det\,SOA} \cdot cos(\omega t) \qquad (2)$$

Where I_{detSOA} is the current detected by SOA, I_{DC} is the average detected current, ΔI_{detSOA} is amplitude of the detected cosinusoidal signal.

The SOA-detector responsivity (R) can be computed from the detected electrical power (P_{detSOA})

$$\Delta I_{det\,SOA} = R \cdot m \cdot \frac{P_{DC}}{a_{in}} \qquad \Rightarrow \qquad R = \sqrt{\frac{2 \cdot a_{in}^2 \cdot P_{det\,SOA}}{m^2 \cdot P_{DC}^2 \cdot Z}} \qquad (3)$$

where Z is the microwave impedance of SOA.

3.2.5 Noise calculation

The optical output from an optical amplifier is composed of an amplified optical signal and an amplified spontaneous emission (ASE) with broad spectral width. Moreover interference is created between ASE components and light signal [Shiraz]. So several types of noises (the shot noise belonging to signal and spontaneous emissions, beat noise between signal and spontaneous emissions, beat noise between spontaneous emission components, thermal noise of the receiver and excess noise belonging to incoherence of the input signal) can be observed, when the output photons are detected by a photo-detector. In the unsaturated region the beat noise between the ASE components dominates. The installation of an optical bandpass filter into the microwave photonics link decreases the noise bandwidth and the equivalent noise power. In SCM system only a single optical carrier is applied, hence small optical bandwidth (1-2nm) should be specified in the link for decreasing the noise build-up.

The noise generated by a SOA acting as a detector is different from the noise generated by a SOA acting as an amplifier or modulator. There are several similar contributions to the total noise power at electrical connection of SOA-detector. However interference between ASE components and light signal is created inside the SOA device. So the noise components originating from the light amplification depend on input parameters as wavelength, input power or driving current with different aspect, than in case of other applications. Shot noise caused by random generation and flow of mobile charge carriers and thermal noise of the load resistor are well known and can be expressed like in a traditional PIN detector [Agraval]. The thermal noise due to electrical amplification has been included as well [Gustavsson].

$$i_{shot}^2 = 2 \cdot e \cdot I \cdot B_0, \qquad i_{therm}^2 = \left[\frac{1}{R_L} + \frac{1-F}{R_N} \right] \cdot 4 \cdot k \cdot T \cdot B_0 \qquad (4)$$

where R_N is a standard 50Ω resistance, F is the electrical amplifier noise figure, k is the Boltzmann constant, T is the temperature, B_0 is the detection bandwidth.

The mean value and the variance of the number of output photons per second due to light amplification process can be calculated. The variance of the detected current due to the photon noise can be obtained from the variance of photons in the amplifier medium. The generated current is proportional to the photon density in the cavity [Gustavsson].

$$i_{ph}^2 = e^2 \cdot (\Gamma \cdot g_m \cdot L)^2 \cdot \overline{\sigma}^2 \cdot B_0 \tag{5}$$

where L is the device length, $\overline{\sigma}^2$ is the photon variance averaged over the amplifier length. In the case of a true traveling wave amplifier (the face reflections are zero) the equivalent noise bandwidth for the beat noise between spontaneous emission components and the equivalent noise bandwidth for spontaneous emission shot noise are equal (Δf) and the variance of the detected current can be calculated [Gustavsson].

$$i_{ph}^2 = e^2 \cdot (\Gamma \cdot g_m \cdot L)^2 \cdot \frac{(G-1)^2}{lnG} \cdot B_0 \cdot \left[\begin{array}{l} 2 \cdot n_{sp} \cdot \dfrac{\lambda}{h \cdot c} \cdot P_{in} + \dfrac{2}{G-1} \cdot \dfrac{\lambda}{h \cdot c} \cdot P_{in} + \\[2mm] + n_{sp}^2 \cdot \Delta f \cdot \left(1 - 2 \cdot \dfrac{G - lnG - 1}{(G-1)^2} \right) + \\[2mm] + 2 \cdot n_{sp} \cdot \Delta f \cdot \dfrac{G - lnG - 1}{(G-1)^2} \end{array} \right] \tag{6}$$

where n_{sp} is the population inversion parameter, $\langle n_{in} \rangle$ is the mean value of the number of input photons per second. The first term of equation represents the beat noise between the signal and the spontaneous mode, the second term represents signal shot noise, the third term represents spontaneous- spontaneous beat noise, and the last term represents spontaneous shot noise over the entire amplifier spectrum.

The signal-to-noise ratio is given by the following equation:

$$SNR = \frac{i_{sig}^2}{i_{ph}^2 + i_{therm}^2} \tag{7}$$

It is of interest to determine the magnitude of each contribution to the total noise in order to see which component dominates at different system parameters. The different noise components depend on the optical signal level with different aspect. The thermal noise, the spontaneous shot noise and the spontaneous beat noise are independent in the unsaturated regime, the signal shot noise and signal- spontaneous beat noise have linear relation with the input optical power. In case of small input optical power one of the constant noises dominates. Then signal shot noise or signal- spontaneous beat noise overcomes this limit. These relationships are illustrated in Fig.12 in which the different noise components and the total noise are calculated as a function of the link loss or input optical power of the SOA-detector. The calculation uses the measured SOA parameters and takes into account the gain saturation effect. Hence the spontaneous shot noise and the spontaneous beat noise start to decrease as the optical gain decreases.

Similar results can be observed in case of constant input optical power as a function of the SOA gain (Fig.12). For low gain values thermal noise and shot noise dominate and for larger

gain the beat noises give the dominating contribution. So the signal-to-noise ratio (SNR) increases up to a certain gain, reaches a maximum, finally it decreases. There exists an optimum amplifier bias point corresponding to maximum SNR of the SOA-detector. Although higher gains would yield higher responsivity, the SNR decreases and it is not desirable for the system.
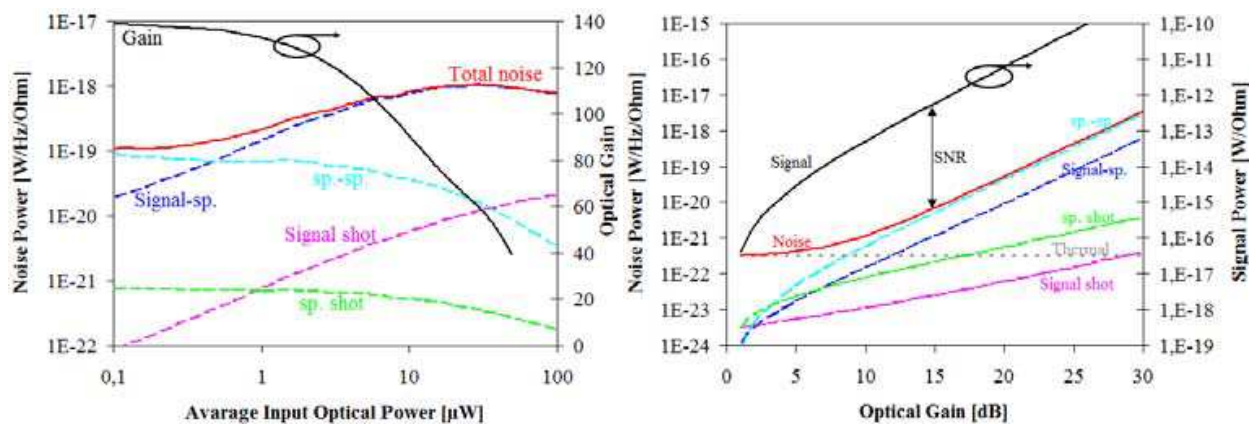

Fig. 12. Calculated noise and signal powers versus input optical power (a) and optical gain (b), calculation based on measured data

3.3 Modulation function
The optical gain of the amplifier depends on the bias current and taking advantage of this effect could be used as an external modulator. The bias current of the SOA is modulated; therefore the material gain and the intensity of the output signal are modulated [Mork]. If small signal current modulation is considered, the electrical signal contains an invariant and a modulation parts, hence the number of charge carriers and photons are also time dependent [Conelly]. The magnitude and purity of the signal depend on the modulation signal, the bias current, the input power and the operation parameters. The SOA modulator requires low modulation power, and the detected electrical power is high because of the optical gain in contrary to the optical insertion loss of other modulators. However the SOA has noticeable optical noise [Udvary1].

3.3.1 Calculation of the realizable modulation depth
The modulation functionality is studied with the following link (Fig.13.). The optical signal from the laser diode is intensity modulated by SOA with time dependent optical gain. The intensity modulated optical signal is detected by traditional PIN photodiode.
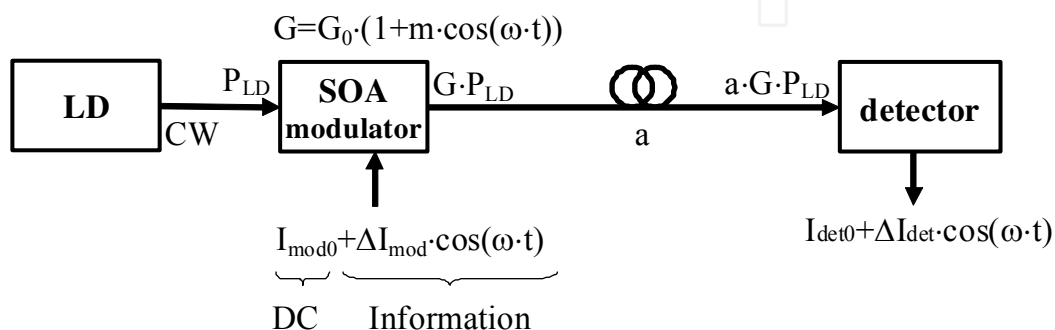

Fig. 13. Simplified block diagram of the link for calculation of modulation behaviour

The modulation operation can be derived based on the slope of the measured optical gain curve (m_d) and the average optical gain (G_0).

The current and the gain of the device are:

$$I(t) = I_0 + \Delta I_{mod} \cdot cos(\omega t) \qquad G(t) = G_0 + \Delta G \cdot cos(\omega t) \tag{8}$$

where I_0 is the constant (dc) current, ΔI is the current modulation amplitude, G_0 is the constant optical gain of SOA, ΔG is the modulation part. Hence the optical signal at the output of the SOA-modulator takes the form

$$P_{out} = G_0 \cdot P_{in} \cdot \left(1 + m \cdot cos(\omega t)\right) \tag{9}$$

where the modulation index (m) is

$$m = \frac{\Delta G}{G_0} = \frac{m_d \cdot \Delta I_{mod}}{G_0} = \frac{m_d}{G_0} \cdot \sqrt{\frac{2 \cdot P_{mod}}{Z}} \tag{10}$$

where P_{mod} is the modulation electrical power, Z is the microwave impedance of SOA.

The output signal of the SOA-modulator is detected by an optical-electrical converter, P_{det} is the detected electrical modulation power

$$P_{det} = \eta^2 \cdot \frac{P_{in}^2}{a^2} \cdot m_d^2 \cdot P_{mod} \tag{11}$$

η is the detection efficiency, a is the optical loss between the SOA and the detector.

The modulation depth is proportional to the slope of the gain curve and the electrical modulation power, but it is in inverse relation to the average optical gain (Eq.16). However, the detected electrical power increases with the modulation power (direct relation), the slope of the gain curve and the input optical power of the SOA-modulator (quadratic relation) increase (Eq.17). Same conclusions can be observed from the experiments.

Naturally, the modulation depth realized by the SOA-modulator can be computed from the measured detected electrical power with the knowledge of the modulation power and the input average optical power of the detector:

$$m = \frac{2 \cdot a^2 \cdot P_{det}}{P_{in}^2 \cdot G_0^2 \cdot \eta_{det}^2 \cdot Z} = \frac{2 \cdot P_{det}}{P_{det}^{opt} \cdot \eta_{det}^2 \cdot Z} \tag{12}$$

Where P_{det}^{opt} is the average optical power at the input of the detector.

Based on this calculation the experimentally realized optical modulation depth is 5-10 percent with sufficiently low (-30dBm) modulation power.

3.3.2 Intensity modulation

Practically, the average optical gain and the slope of the optical gain - bias current curve determine the optimum working state of the SOA as a modulator. The curve can be divided into three parts (Fig.14.). In the first one the amplification just starts and it is not effective, the second one is the almost linear region and after it the slope of the optical gain starts to decrease. The middle of linear region of this curve should be chosen for operation point, because of the low static non-linear distortion effect and the high slope [Udvary2].

Fig.14. shows the measured optical gain and modulation behavior of the SOA-modulator versus bias current. The three regions are well seen in this figure, too. The injection current

is not enough for the expected work and the detected power is low in the first part. The power is near constant in the second linear part and after it the detected product starts to decrease because the slope of the gain curve falls. The lower curve at modulation behavior figure represents the result without input optical power, i.e. just the amplified spontaneous emission power (ASE) produces the modulated signal and the broadband O/E (optical-to-electronic) converter can detect this poor fluctuation. This effect can be dramatically decreased by a narrow band optical bandpass filter.
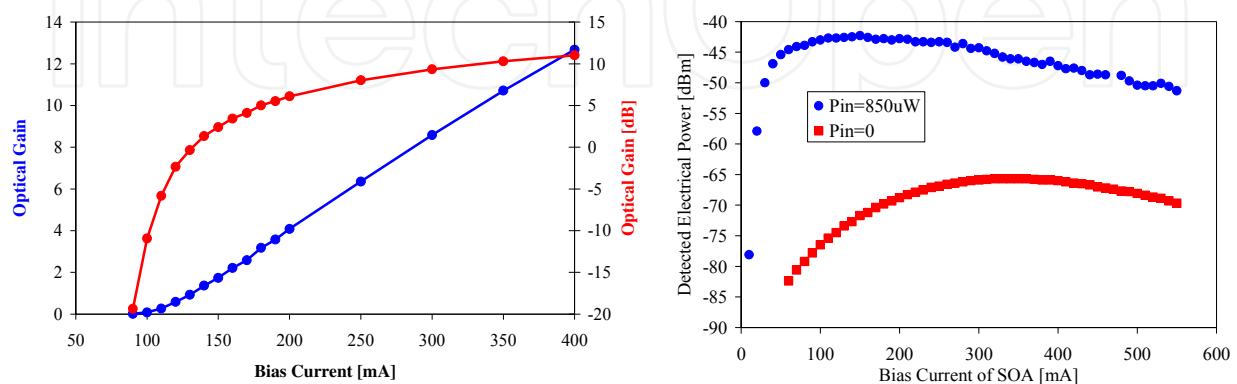
Fig. 14. Measured Optical Gain (a) and Modulation behaviour (b) of SOA-modulator versus bias current of the device. Wavelength=1550nm, Temperature=20°C, Modulation power=-30dBm, Modulation frequency=400MHz

The modulation bandwidth is limited by the speed at witch the carrier density can be changed, this is usually limited by the spontaneous lifetime of the carriers in the SOA (in the nanosecond range). The lifetime in the presence of a strong, saturating input signal is reduced due to stimulated recombination. The real speed depends on the structure of the device, but in general it is larger than 10GHz speed.

3.3.3 Linearity

Degradation of the transmission system will occur due to the crosstalk between the subcarriers (nonlinearity) and noise expansion (ASE). In linear regime the SOA modulator shows low nonlinearity because the noise generated by the SOA will dominate in the system. The intermodulation products overcome the noise floor in case of extraordinary high modulation indices and in the saturated operating region.

The nonlinearity causes intermodulation by different order mixing products. In practice, it is assumed that the transfer function of the device has only linear and cubic terms, because the even order terms do not produce mixing products falling into the transmission band and from order 5 the level of mixing products supposed to be very small.

In the two-tone intermodulation experiments the SOA was biased and modulated by the sum of two microwave signals. The output noise (P_{noise}) and signal levels were measured for the fundamental (P_1), the second (P_{sec}) and the third (P_{th}) order mixing products.

For characterizing the nonlinearity the third order intercept point (IP3) or the spurious suppression in dBc is used. However, for high quality signal transmission a high linearity is not sufficient because the noise has to be low as well. Therefore, the spurious free dynamic range (SFDR) is a better characteristic. It is dependent both on the linearity and noise, it is higher when the linearity is high and the noise is small. In personal communication systems

$72-83$ dB$\cdot$Hz$^{2/3}$ SFDR is required [Olshansky]. The determination of SFDR, IP2 and IP3 are presented in Fig.15.
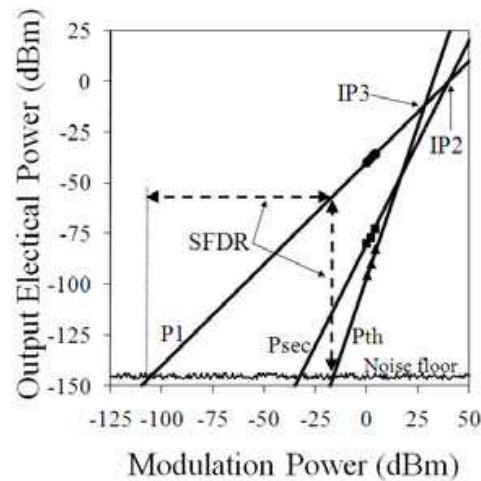

Fig. 15. Determination of SFDR, IP2, IP3.

Modulation frequencies=199, 200MHz, Modulation Power=4dBm, Input Optical Power=1mW, without Isolators, Temperature=20°C

$$IP2[dBm] = 2 \cdot P_1[dBm] - P_{sec}[dBm]$$

$$IP3[dBm] = \frac{1}{2} \cdot \left(3 \cdot P_1[dBm] - P_{th}[dBm]\right)$$

$$SFDR = \frac{P_{in}(P_{th} = P_{noise})}{P_{in}(P_1 = P_{noise})} = \frac{P_1(P_{th} = P_{noise})}{P_{noise}}$$

$$SFDR[dB] = \frac{2}{3} \cdot \left(IP3[dBm] - P_{noise}[dBm]\right)$$

The experimental work was done on different types of SOAs. The presented results characterize a commercial SOA having 13 dB of small signal gain, 15dBm of saturation power, 100nm of optical bandwidth, 300mA of bias current. All the measuring instruments were checked to have higher dynamic range and better linearity than the value expected from the SOA-modulator. 7% modulation depth was applied, because the modulation indices are usually less than 10 % in typical SCM systems. However, it was also checked for a wide range of modulation depth (3-30%).

The nonlinear behavior depends on several parameters [Marozsak]. Fig.16. shows the noise level, IP3 and SFDR versus bias current. The graph can be divided into three parts. First, the SOA is near the transparency, the nonlinearity is high; hence the IP3 and the SFDR improve as it approached the near linear range. In the second part the modulation and nonlinear products don't change significantly but the noise level rises, hence the SFDR decreases. Finally, the intermodulation products start rising and the degradation of the SFDR is faster. The shapes of the curves are similar for the results estimated from the one tone simulations. The reason of some difference (some dB) in the exact values is that for the measurements the SOA device's internal parameters were not available. So we could only use estimated parameters for the simulations.
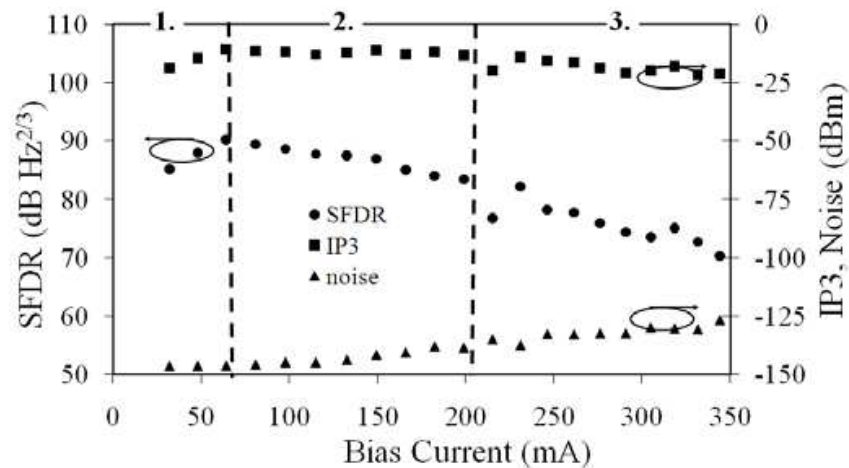
Fig. 16. Nonlinear behavior of SOA modulator versus bias point. Modulation frequencies=199, 200MHz, Modulation Power=4dBm, Input Optical Power=1mW, without Isolators, Temperature=20°C

By injecting more optical power, the noise floor reduces due to the amplified spontaneous emission (ASE) reduction in saturated regime. Same time the optical gain – bias current curve is more linear. The combination of these two factors allows us to obtain a better SFDR at high input optical power.

The linearity is temperature sensitive, because the operation of semiconductor devices depends on the temperature. The degradations of SFDR and IP3 are about $2dB \cdot Hz^{2/3}$ and 3dB for 10°C temperature change (Fig.17.).
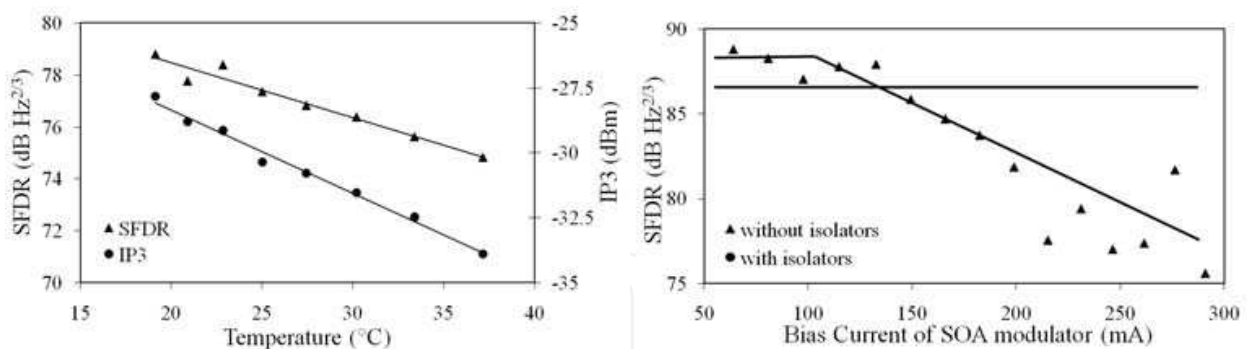
Fig. 17. Nonlinearity dependence on the temperature and optical reflection Wavelength=1550nm, Input Optical Power=1mW, Bias Current=50mA, Modulation frequencies=199, 200MHz

In short distance RoF link, the level of optical reflection is usually determined by the optical detector. The system will be more instable in case of strong optical reflection (without optical isolators), and larger SFDR degradation can be observed as seen in the Fig.17. The change of the SFDR is caused by two different effects (Fig.18.). The noise level of the device increases as a function of the bias point, the degradation is more significant without optical isolator. On the other hand the level of the nonlinear product will fluctuate in case of strong reflection.
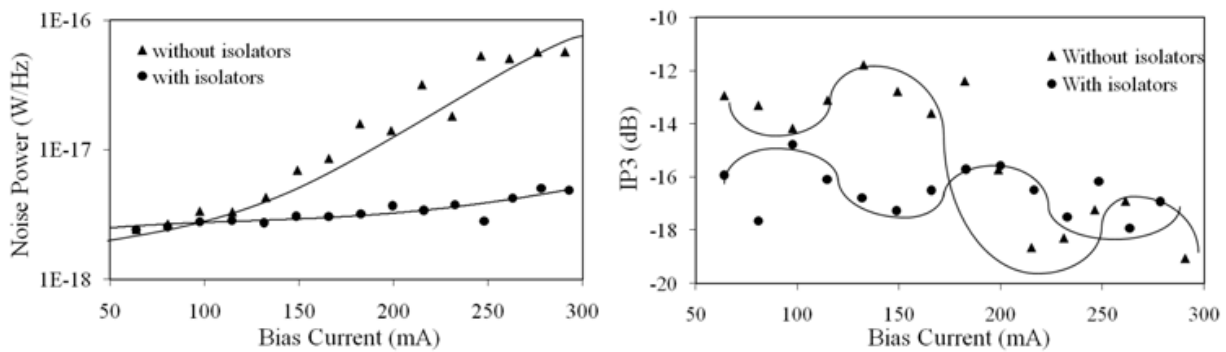
Fig. 18. Levels of noise and intermodulation products depends on the optical reflection. Wavelength=1550nm, Frequencies=199, 200MHz, Input Optical Power=1mW, Temperature=20°C

3.4 Dispersion compensation in RoF systems

Compensating dispersion penalty is a key problem when next generation Radio-over-Fiber networks are built. Several techniques have been proposed to overcome dispersion effect. An alternative method is presented to overcome the RF carrier suppression effect in optical links based on the joint effect of SOA chirp, chromatic dispersion and nonlinearities of the optical fiber. The results show that the frequency notches caused by the dispersion-induced carrier suppression effect may be sharply alleviated and the performance of the transmitted digital signal can be improved.

The SOA dispersion compensator has the advantage that it is a loss-less, wide band solution with robust operation. It is more efficient than midway optical phase conjugation or self phase modulation effect introduced by the fiber. It offers optical amplification compared with high insertion loss of dispersion compensation fiber. It has high bandwidth (30-35nm), hence it is transparent for optical or electrical carrier variation and more insensitive for environmental and system parameters than Fiber Bragg Grating. It is semiconductor based device, which can be easily integrated with semiconductor optical source. So it doesn't demand expensive and complex optical device (like SSB Mach-Zehnder modulator), just an additional integrated section is necessary in the optical source. Additionally the operation of the device can easily be optimized by bias point and input optical power control.

3.4.1 Basic operation

When the incoming optical power of the laser amplifier is intensity modulated, the optical gain is affected in both magnitude and phase via the modulation of the complex refractive index caused by the electron density. Consequently, in SOA the optical signal becomes amplitude modulated (AM) and phase modulated (PM). It can be modelled using the Linewidth Enhancement Factor (LEF=Henry factor=α factor) approximation. Measurements of LEF can are found in the literature and have shown that LEF is not a mere constant factor, but it is for instance a function of bias current, wavelength and input optical power. In the unsaturated region the LEF value ranges from 2 to 7 for GaAs and GaInAsP conventional lasers and from 1.5 to 2 for quantum well lasers [Occhi]. However, the chirping parameter which is positive for light sources and unsaturated optical amplifiers is negative for saturated amplifiers [Watanabe]. It cancels the positive chirp-parameter of modulator, causing asymmetrical optical power between the sidebands [Lee] and the optical amplification causes RF signal gain [Marti]. However the SOA adds noticeable noise to the system.

3.4.2 Calculation and simulation results

The frequency transfer function of the optical link:

$$H_{\text{SOA}+link}(f) = cos\left(\frac{\lambda^2 \cdot D \cdot \pi \cdot f^2 \cdot L}{c}\right) - LEF \cdot sin\left(\frac{\lambda^2 \cdot D \cdot \pi \cdot f^2 \cdot L}{c}\right) +$$
$$+ j \cdot LEF \cdot \frac{f_c}{f} \cdot sin\left(\frac{\lambda^2 \cdot D \cdot \pi \cdot f^2 \cdot L}{c}\right) \tag{13}$$

Where D is the fibre dispersion parameter, L is the fibre length, f is the modulation frequency, c is the speed of light in vacuum, λ is the operating wavelength. For simplicity the linear loss and delay of the fibre are neglected.

The calculated RF responses of 400 km fibre for different chirp parameters of the optical transmitter are depicted in Fig.19. All the results have been calculated for an optical input power of 0 dBm in order to reduce the influence of the nonlinear effects in the fibre. By comparing the results to the reference case of a zero-chirp situation (*LEF*=0), for *LEF*<0, the achievable bandwidth increases.
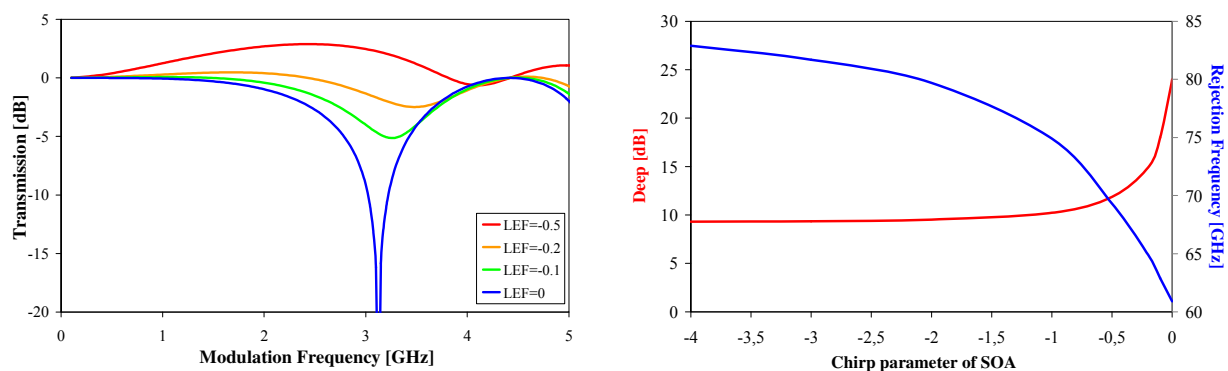
Fig. 19. Calculated quality of MW/MMW transmission for different SOA and system parameters, Optical wavelength=1550nm, D=16.8 ps/(nm·km)
(a) Transfer function with different chirp parameter of SOA, fiber length=100km
(b) Rejection frequency and the deep versus chirp parameter of SOA, fiber length=1km

In real radio over fibre systems the radio frequency carrier is modulated by digital information. The above presented dispersion compensation technique affects the eye diagram, the BER (Bit Error Rate) and the EVM (Error Vector Magnitude), which are the important quality factors of signal transmission. If the subcarrier frequency is close to one of the frequency notches caused by dispersion the eye diagram closes, the BER and EVM decay, the communication deteriorates or lost. Applying the SOA compensator the eye diagram opens, low BER is obtained and EVM can greatly benefit from the improved link performance. The simulations were executed with different modulation schemes on radio-over-fibre systems and VPI software was applied. Fig. 20 presents the quality of 4 QAM (quadrature amplitude modulation) radio signal transmission with different SOA chirp parameter, it shows the Symbol Error rate improvement applying SOA dispersion compensator. The EVM and SER increase versus chirp parameter. If the subcarrier frequency is close to the frequency notch, the communication lost. Applying a SOA dispersion compensator the constellation diagram can be detected, but the diagram rotates because of the additional phase modulation generating the SOA chirp.
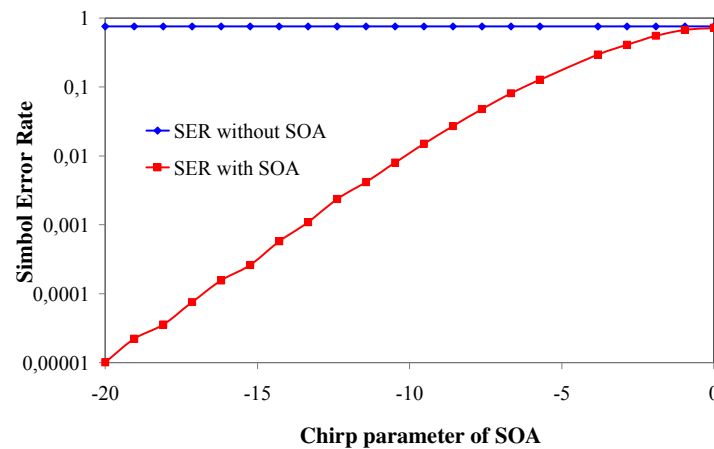
Fig. 20. Simulated Symbol Error Rate at frequency notch versus chirp parameter of SOA, L=500m, fsubcarrier=60GHz, modulation= 2048Mbps, 4QAM, without and with SOA

3.4.3 Experimental work

The calculated and simulated results can be verified by experimental work. The SOA under test was driven by different bias (dc) currents. The polarization state of the incoming optical power was optimized by polarization controller. The harmful effect of the optical reflection was eliminated by optical isolators. The required optical power and wavelength were produced by a tuneable laser source. The intensity modulated optical signal was detected by a photodetector. The setup was controlled by a computer program, hence the measurement parameters were carefully set by the program and the measurement results were processed and stored.

The measured RF responses of 50km fibre for different operation points of SOA are depicted in Fig. 21. By comparing the results to the reference case of a zero-chirp situation (*LEF*=0), for *LEF*<0, the achievable bandwidth increases. As the SOA bias current (optical gain) increases the frequency notches of the RF response are reduced and shifted to higher modulation frequencies. Based on the results, we may conclude that the interplay of chirp generated by the saturated SOA and chromatic dispersion enables a significant reduction of the dispersion-induced effect.
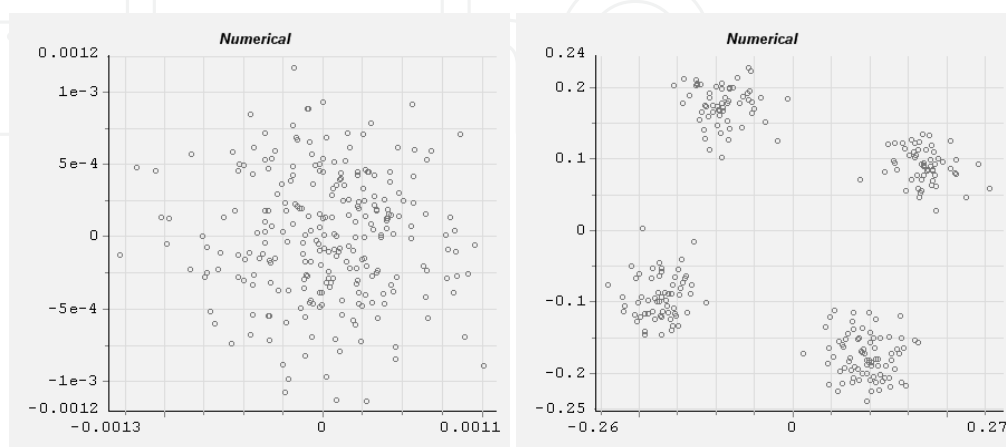

Fig. 21. Simulated constellation diagrams (a) without SOA, (b) with SOA compensator, L=500m, fsubcarrier=60GHz, modulation= 2048Mbps, 4QAM
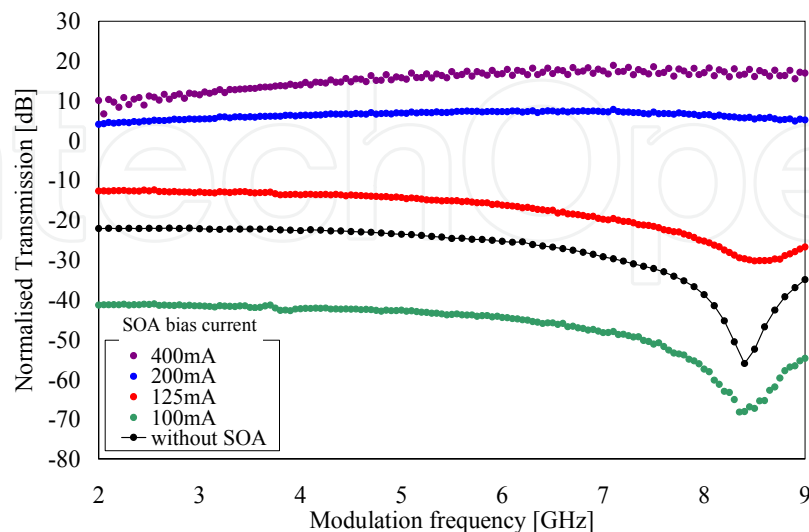
Fig. 22. Measured RF responses of the optical link for different SOA parameters
Length of the optical fiber=50km, Length of the reference optical fiber=4m, Optical
wavelength=1550nm, bias current of the SOA=400mA, 200ma, 125mA, 100mA, Optical
Gain=15dB, 13.5dB, 4,5dB, -9.5dB

4. Conclusion

This book chapter reviews the application of multifunctional Semiconductor Optical
Amplifier in microwave photonics optical communication links. The device shows proper
performance during the theoretical and experimental study. The noise, the linearity, the
bandwidth and the dispersion effect of the multifunctional SOA applied in an optical link
are studied. SOAs are potential candidates for modulation and detection tasks in RoF
systems as their capabilities for detection/modulation, and amplification at the same time.
So, cost effective designs are possible only employing one device at the subscriber's unit. On
the other hand, the multifunctional SOA can improve the performance of microwave
photonic links thanks to its dispersion compensation function.

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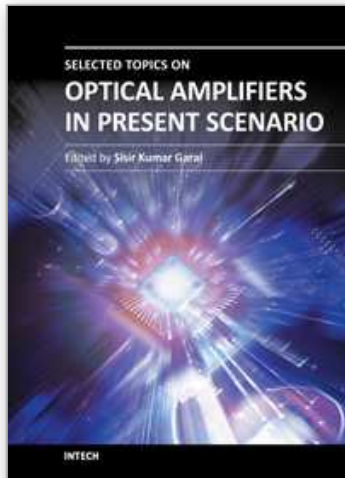
Selected Topics on Optical Amplifiers in Present Scenario
Edited by Dr. Sisir Garai

With the explosion of information traffic, the role of optics becomes very significant to fulfill the demand of super fast computing and data processing and the role of optical amplifier is indispensable in optical communication field. This book covers different advance functionalities of optical amplifiers and their emerging applications such as the role of SOA in the next generation of optical access network, high speed switches, frequency encoded all-optical logic processors, optical packet switching architectures, microwave photonic system, etc. Technology of improving the gain and noise figure of EDFA and, the study of the variation of material gain of QD structure are also included. All the selected topics are very interesting, well organized and hope it will be of great value to the postgraduate students, academics and anyone seeking to understand the trends of optical amplifiers in present scenario.

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