Semiconductor Optical Amplifiers in Access Networks

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Abstract
We review the uses of semiconductor optical amplifiers (SOAs) in passive optical networks (PONs). SOAs can be used to extend the reach and split ratio of the network. Reflective SOAs can be used as wavelength-agnostic modulators in Wavelength Division Multiplexed PON.

Introduction

Optical fiber is being installed in access networks worldwide to quench the insatiable thirst of network users for more bandwidth. In some parts of the world, such as India, this is happening at an accelerated pace [1].

The network architectures most often encountered in modern fiber-to-the-home (FTTH) installs are power-splitting passive optical networks (PONs), such as broadband PON (BPON) and Gigabit PON (GPON) as defined by the Full Service Access Network (FSAN) initiative, and Ethernet-Based PONs (EPON and GEPON) as defined by the Ethernet in the First Mile (EFM) initiative [2,3].

Taking GPON as an example, the standard as defined by the International Telecommunication Union in its ITU-T G.984.x series provides for downstream transmission – from the optical line terminal (OLT) in the central office (CO) to the optical network units (ONUs) at the customer premises – at a bit rate of up to 2.5 Gb/s and a nominal wavelength of 1490 nm, while the upstream transmission usually takes place at a bit rate of 1.25 Gb/s and a wavelength of 1310 nm. With a passive optical splitter installed in the field, downstream data is transmitted to up to 128 ONUs using time division multiplexing (TDM), while the system employs a time division multiple access (TDMA) protocol for the upstream direction (see Fig. 1).

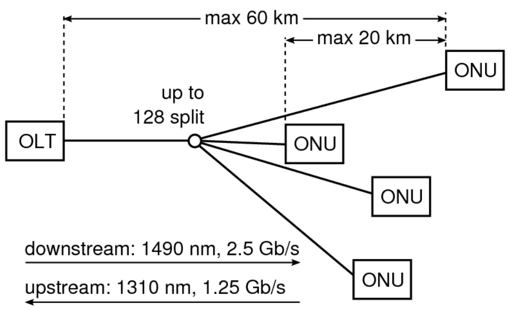

Fig. 1. Gigabit passive optical network (GPON) physical network architecture. The standard supports a maximum reach of 60 km and a split ratio up to 128. However, in practice the optical power budget typically allows for a reach of 20 km and a 32 split. OLT: optical line terminal; ONU: optical network unit.

GPON has a logical reach of 60 km, with a differential reach between ONUs of at most 20 km. These distances are determined by the limits of the TDMA protocol. In practice, however, most commercial systems support an optical loss budget up to 28 dB, allowing for a physical reach of 20 km and a split of up to 32.

A potential technology for next generation PONs is the use of wavelength division multiplexing (WDM) to support much higher bandwidths without increasing the data rate [4]. The majority of proposed realizations replace the passive splitter in the field with a passive wavelength router, such as an arrayed waveguide grating (AWG). An active area of research targets so-called colourless ONUs, that allow a single type of ONU for transmission of any of the upstream wavelengths used in the WDM-PON.

Extended PON

Semiconductor optical amplifier (SOA) technology can be used in two major ways in next generation PONs: To increase the optical power budget between the OLT and the ONU, and for colourless upstream transmission.

For network operators, extending the range and split ratio of a PON is an attractive proposition, because it combines local access and backhaul networks, reducing the number of large local exchanges, which may lead to substantial cost savings [5]. SOAs are a suitable choice for PON extension because of their ability to provide gain in the desired wavelength bands, their fast gain dy-

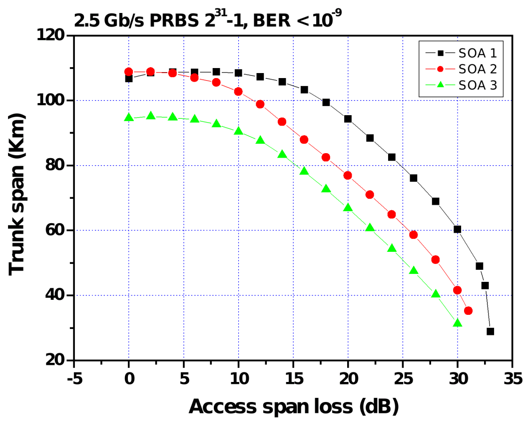

Fig. 2. Trunk span length and split loss allowed in a SOA-amplified PON [6]. The worst-case (i.e., upstream) power budget is shown. The three limiting regimes of noise figure (determining maximum split and access span loss), gain, and output power (determining trunk fiber length) are visible. Curves are shown for three different SOAs at bit error rates of 10^{-9}.

namics that enable dealing with burst traffic as is present in particular in the upstream direction, and their low power requirements [6].

From an optical budget perspective, the best location of the PON amplifier is in-line, approximately midway the total optical loss between OLT and ONU. In practice, this usually means co-location with the passive splitter. A compact PON extender box could be sited on a pole or in a small cabinet [7].

We need to consider the upstream direction in order to determine what reach and split extension can be reached, because the transmission fiber is more lossy at 1310 nm. The maximum length of the trunk fiber (from the amplifier site to the OLT) is then determined by the output power that the SOA can deliver, while the maximum access span loss (the fiber loss from the ONU to the passive splitter, plus the splitter loss) is determined by the noise figure of the SOA. Of course, the overall power budget enhancement is limited by the SOA gain. These three regimes can be observed in Fig. 2, which shows that a total reach of 60 km and a 128 split (corresponding to 21 dB of splitting loss) are feasible.

An additional benefit of using a SOA PON extender can be obtained by using the upstream SOA as a power equalizer for varying burst powers originating from the fact that the ONUs are located at different distances from the OLT. Equalization can be accomplished either by controlling the injection current of the SOA or by using a SOA in gain saturation [8].

The influence of unfiltered amplified spontaneous emission (ASE) noise of the SOAs introduces a loss of extinction ratio in the receivers [9] that becomes a significant source of transmission penalty at high bit rates. It has been shown that a specially shaped filter can provide ASE attenuation outside a narrow bandwidth as would be appropriate for next generation 10 Gb/s systems, without completely blocking legacy low bit rate signals outside this band, that do not suffer appreciably from this penalty. Such a configuration provides a suitable upgrade path for hybrid 1 Gb/s / 10 Gb/s systems [10].

Another next generation upgrade path is to include the wavelength dimension using WDM-PON, e.g., by adding three downstream broadcast coarse WDM (CWDM) channels [11], or by multiplexing four complete TDM PONs on four downstream and four upstream CWDM channels [5,12].

Colourless ONU

A WDM PON using multiple upstream wavelengths can additionally benefit from SOA technology by using the devices as colourless upstream transmitters. In this case, the wavelengths are all sourced by the OLT, and a SOA in the ONU is used as a wavelength-agnostic modulator; a reflective SOA (RSOA) configuration is typically used, in which the amplifier has only a single pigtail [13].

Thanks to the fact that the RSOA can be used in gain saturation, uncooled operation is possible [14]. The RSOA can be seeded either by CW light originating from the OLT, or by using an appropriately coded downstream signal [15]. The high off-state extinction provided by the SOA is essential for preventing in-band crosstalk penalties at high split ratios [16]. Using electronic equalization, upstream bit rates up to 10 Gb/s can be reached [17].

Summary

The wavelength-agile and dynamic properties of SOAs make them suitable as components in upgraded passive optical networks. In-line SOAs extend the range and split of the access network, and enable GPON to operate at its maximum logical reach and split. RSOAs function as colourless modulators in wavelength-agnostic ONUs, allowing a single type of ONU to be used for any upstream transmission channel in a WDM-PON.

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