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# TWC and AWG based optical switching structure for OVPN in WDM-PON*

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With the rapid development of optical elements with large capacity and high speed, the network architecture is of great importance in determing the performance of wavelength division multiplexing passive optical network (WDM-PON). This paper proposes a switching structure based on the tunable wavelength converter (TWC) and the arrayed-waveguide grating (AWG) for WDM-PON, in order to provide the function of opitcal virtual private network (OVPN). Using the tunable wavelength converter technology, this switch structure is designed and works between the optical line terminal (OLT) and optical network units (ONUs) in the WDM-PON system. Moreover, the wavelength assignment of upstream/downstream can be realized and direct communication between ONUs is also allowed by privite wavelength channel. Simulation results show that the proposed TWC and AWG based switching structure is able to achieve OVPN function and to gain better performances in terms of bite error rate (BER) and time delay.

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As optical devices technologies develop rapidly, great progress has been achieved in the field of passive optical network (PON) technologies. In the evolvement of the wavelength division multiplexing based PON (WDM-PON) technology, the architecture of WDM-PON plays a key role to determine its performance directly[1-4]. Following this trend, great effort has been made to develop optical devices with better performance and to introduce them into WDM-PON field.

With the rapid development of optical devices technologies, the tunable wavelength converter (TWC) technologies show great potential in the PON field, where the tuning time of tunable wavelength converter is able to achieve the nanosecond level now[5,6]. So far, the performance of TWC has already satisfied the requirement on operation or response speed proposed by PON. Therefore, better dynamic ability and higher capacity of PON could be enabled greatly by introducing this technology[7-9]. As another new technology of optical element, arrayed waveguide gratings (AWGs) are one kind of the commonly used devices for wavelength multiplexing[10]. However, in silicon, AWGs have always lagged in performance compared with the other techniques, such as silica[11] and InP[12]. Silicon AWGs can be much smaller because of the high refractive index contrast, while the same high index contrast gives rise to phase errors and other parasitic errors which contribute to the overall crosstalk of the device. In general, silicon AWGs achieve crosstalk levels of -20 dB, while the best devices show -25 dB crosstalk[13,14].

Benefitting from advance of TWC and AWG technologies, a TWC based WDM-TDM PON has been reported[15]. However, it fails to realize the OVPN function. The OVPN has been considered by allowing direct communication between ONUs with private wavelengths[16].

This paper presents a TWC and AWG based switching structure for OVPN in WDM-PON, where the TWC and AWG are fully used to realize a switching structure. Simulation results show great feasibility of this structure and demonstrate better performances in terms of communication security, capacity and bite error rate.

The tunable wavelength converter has been widely used in optical network node design, which is able to generate a configurable wavelength for an incoming optical signal. Generally, the tunable wavelength converter includes a tunable laser, a semiconductor optical amplifier (SOA) and a Mach-Zehnder Interferometer (MZI). The conversion is performed by the SOA which receives the tunable laser wavelength and the data as an input and outputs the data in the selected wavelength. The SOA is followed by the MZI which works as a filter to generate reshaped and clean pulses of the tuned wavelength. Moreover, it is shown that the wavelength conversion can be achieved at 160 Gbit/s and the reconfiguration time is at the level of nanoseconds.

AWG is a planar-waveguide devise execution of high-order transmission gratings. Arrayed waveguides

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are fabricated in silica, plastic, silicon, or III-V semiconductor materials, such as indium phosphates. AWG as a planar waveguide device, it can be fabricated monolithically and integrated with other components.

AWGs are commonly used as optical multiplexers in wavelength division multiplexed (WDM) systems. These devices are capable of multiplexing a large number of wavelengths into a single optical fiber, thereby increasing the transmission capacity of optical networks considerably. This remarkable device has been made using several planar-waveguide technologies and has found a variety of applications in WDM lightwave systems. AWGs are based on the principles of diffractions. An AWG device is sometimes called as an optical waveguide, a waveguide grating router or a phase array. An AWG device consists of an array of curved-channel waveguides with a fixed difference in the lengths of optical path between the adjacent channels. An AWG is a generalization of the Mach-Zehnder interferometer.

The TWC and AWG based switching structure for the OVPN in WDM-PON is given in Fig.1. As Fig.1 shows, the optical switching structure (OSS) mainly includes four TWC modules, one 4×4 AWG, one splitter and four optical ports. This OSS works between OLT and ONUs and can be located at local or remote place.

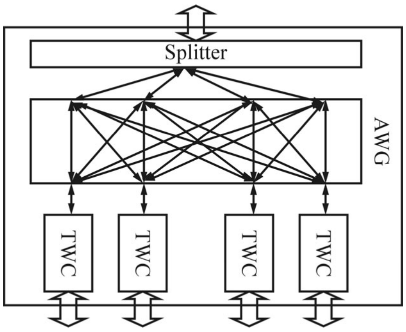

**Fig.1 The optical switching structure**

In this switching structure, the tunable wavelength converters based on SOAs and MZI have been applied. Due to input signal wavelength changes the reflectivity of the SOA waveguide by consuming the carriers, the input continuous wave light for detection has been modulated in phase. The MZI transfers PM to AM, so the output light for detection carries AM signal, which means that wavelength has converted. The task of TWCs is to transform optical signals into a wavelength from an ONU into another one wavelength. Each TWC module corresponds to an optical port, and provides up to 32 wavelengths for ONUs. Benefitting from the TWC, the power and the optical signal to noise ratio (OSNR) of optical signal can be improved.

As one of key elements, the 4×4 AWG is adopted in this optical switching structure, which is mainly responsible of switching between OLT and ONUs or among ONUs. And there are 4 pairs of ports in this AWG. In each pair of ports, one wavelength channel is kept for traditional OLT-ONUs and the other three channels are used as loop-back channel for ONU to ONU. In this optical switching structure, the communication between OLT and ONUs is kept through the approach of traditional WDM-PON, while wavelength conversion and loop-back are used to realize direct communication among ONUs.

Combining advantages of both tunable wavelength converter and arrayed waveguide grating, the optical virtual private network (OVPN) can be realized with this proposed optical switching structure. Through this OSS, direct communication among ONUs without going through OLT can be achieved. In this OSS, the TWC and the AWG work together as a so-called "wavelengths poll", where each ONU under the same port can be allocated a wavelength. When an ONU needs to communicate with another ONU, the TWC will transform its signal to the wavelength of this corresponding ONU, and this wavelength will go through the "loop-back" channel of the AWG to be received by the aimed ONU. Thus, the OVPN function among ONUs can be realized.

Enhanced by this OSS, the WDM-PON is able to offer an extra degree of more scalability, since each TWC can support 32 ONUs maximally. That means the whole WDM-PON system can totally provide access to up to 128 ONUs, which greatly enlarges the system capacity.

To evaluate the feasibility and performance of this optical switching structure, theoretical analysis is made in this section. As bite error rate (BER) is one of key factors of communication system, BER is selected to evaluate this proposed OSS.

Generally, the optical signal is unavoidable to suffer from various physical layer impairments, which would lead to the worse BER. In the non-ideal optical network, physical layer impairments can be divided into two categories: linear impairments and nonlinear impairments. In fact, various kinds of physical layer impairments can be transformed into OSNR model in Ref.[17], and those impairments include amplified spontaneous emission (ASE), polarization dependent loss (PDL) and channel uniformity (CU).

The OSNR value considering ASE caused by the TWC can be obtained via:

$$OSNR_{\mathrm{out}} = -10\lg\left[10^{-\left(\frac{P_{\mathrm{in}1}-NF_1-10\lg(hvB)}{10}\right)}\right], \tag{1}$$

where $P_{\mathrm{in}}$ is the input power of TWT, $NF$ is the noise factor of TWC, $v$ is the working frequency of light wave, $h$ is the Planck constant and $B$ is the bandwidth. The OSNR degradation due to PDL is given by:

$$OSNR_{PDL} = \sqrt{\frac{8}{3\pi}}\left(\sum_i PDL_i^2\right)^{\frac{1}{2}}. \tag{2}$$

And the OSNR degradation caused by CU can also be got through:

$$OSNR_{CU} = CU_1 + CU_2 + \ldots + CU_n, \tag{3}$$

where the $CU_i$ represents the $CU$ value of optical element $i$. Thus, the total OSNR model can be drawn by combining Eqs.(1)-(3):

$$OSNR_{\text{total}} = OSNR_{\text{out}} - OSNR_{CU} - OSNR_{PDL} . \tag{4}$$

On the basis of the OSNR normalization mentioned above, the BER normalization model can be built by:

$$BER = \frac{1}{2}\operatorname{erfc}\left(\frac{Q}{\sqrt{2}}\right), \tag{5}$$

where

$$Q = \frac{2\rho}{\sqrt{M} + \sqrt{M + 4\rho}} ,$$

$$M = 2BT ,$$

$$\rho = nB_{\text{ref}} T \times OSNR_{\text{total}} . \tag{6}$$

With the maturation of optical performance monitoring technologies, the approach used to calculate BER of the proposed OSS has been well established.

To evaluate validity of the proposed OSS, a WDM-PON system test-bed is built in this paper, with 4 wavelength-converters in the switch structure and 8 or 16 wavelengths. Moreover, 16 or 32 ONUs are equipped under each TWC module. As for AWG, the center wavelength is 1 550.83 nm, wavelength channel spacing is 0.8 nm, 3-dB bandwidth is about 0.476 nm, insertion loss is 13-15 dB, and crosstalk is about -21 dB. Moreover, wavelength tunable converted signal over 40 nm is set with around 2.5 dB power penalty. The parameters in this test are as follows: maximum cycle time is 2 ms, speed of OLT is 40 Gbit/s, the guard time is 1 μs, and buffering queue size is 50 MB.

In this simulation, the comparison is made between the proposed OSS based WDM-PON and the AWG based WDM-PON in Ref.[16]. Simulation results are shown in Fig.2 and Fig.3, in terms of BER.

The comparison of BERs with different received powers is given in Fig.2. As the power decreases, total performance of BER gets worse. And obviously, the OLT-ONU case has higher BER than the ONU-ONU case. Overall, the proposed structure has better BER performance than the other one, both in OLT-ONU communication and ONU-ONU direct communication.

Similar results are also shown in Fig.3, which is BER versus distance. As the distance is getting longer, BER performances of both structures degrade seriously. Not only in the OLT-ONU case but also in the ONU-ONU case, the proposed structure works better than the other one.

Combining simulation results of Fig.2 and Fig.3, the proposed optical switching structure of this paper shows better BER performance when compared with the other one. That is because the OSS is able to improve the power of signal and the OSNR by using TWCs.

The comparison of time delays of communications between ONU and ONU is given in Fig.4. This comparison is conducted among three kinds of conditions: the OSS based WDM-PON, the AWG based WDM-PON and traditional WDM-PON. Obviously, the traditional WDM-PON shows the worst result, because the ONU-ONU communication must go through OLT in this case, which will cause time delay in the OLT. And the others have similar performance and work better than the traditional one. That is because direct communication between ONUs without OLT is able to save time greatly, while the traditional one fails.

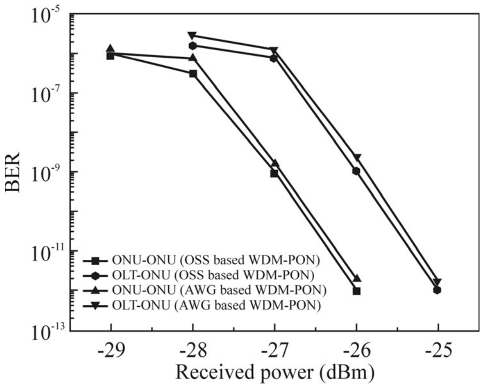

**Fig.2 Comparison of BERs with different received powers**

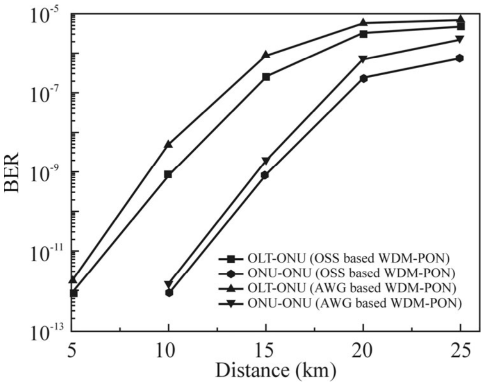

**Fig.3 Comparison of BERs with different distances**

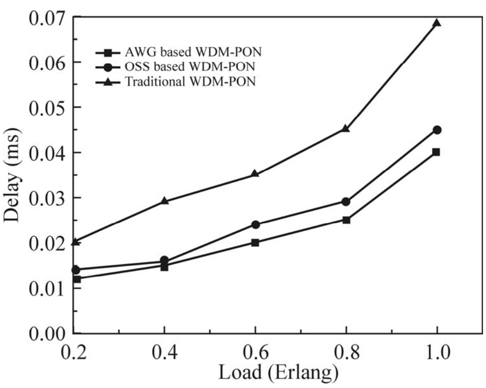

**Fig.4 Time delay comparison of ONU-ONU communication**

In this paper, a TWC and AWG based optical switching structure is proposed and designed for OVPN in WDM-PON, by making full use of the TWC and the AWG. Through this OSS, the TWC and AWG work together to provide OVPN, and the direct communication among ONUs could be achieved. Simulation results show that the proposed OSS for OVPN works well with better BER and delay time performance.

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