A multiple star WDM-PON using a band splitting WDM filter

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Abstract: We propose a multiple star wavelength division multiplexing-passive optical network (WDM-PON) to serve several subscriber groups located at a widely distributed area. The architecture based on a band splitting WDM (BSWDM) filter separates upstream and downstream bands to several sub-bands and assign them to different subscriber groups. As a result, it enables to use a single type AWG for second stage splitting points. Thus, it provides color-free outside plant and simplifies management issues. The proposed architecture also provides pay as you grow feature.

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References and links

1. Introduction

Recently, passive optical networks (PONs) have been extensively investigated to solve the first mile bottleneck caused by limited bandwidth of the copper cables [1]. In designing the PON, an outside plant (OSP) architecture established a single splitting point (a single star) or multiple splitting points (a multiple star). A TDM-PON can easily accommodate a multiple star architecture with a series of optical power splitter. However, it is not straightforward in the wavelength division multiplexing (WDM)-PON. This is because we need to use a WDM
multiplexer/demultiplexer (Mux/Demux). Therefore, the WDM-PON can be considered as a single star architecture that has lack of flexibility to serve cluster of customers at a different location. The single star architecture also causes high up-front costs because of installation of WDM Mux/Demux at the beginning of deployment. To solve these issues, some solutions have been proposed [2, 3]. But, as the 1st stage splitting ratio is increased, the configuration of filter becomes complicated. It also brings about increase of an insertion loss and decrease of transmission length/system margin. More importantly, these architectures require arrayed waveguide gratings (AWGs) which have diverse transmission characteristics at the different location. In other words, multiple type of AWG should be used at the 2nd stage splitting point. Thus, the OSP is not color-free (here, color-free means a wavelength independent) and it is difficult to manage the OSP.

In this paper, we propose and demonstrate a multiple star WDM-PON based on a band splitting wavelength division multiplexing (BSWDM) filter. A single type AWG is used at all 2nd stage splitting points to realize a color-free OSP. In addition, the insertion loss is independent of the splitting ratio of the 1st stage splitting point. The proposed architecture also provides pay as you grow feature to reduce up-front costs of the WDM-PON.

2. Wavelength plan of BSWDM filter

We show the proposed multiple star WDM-PON architecture employing BSWDM filters in Fig. 1. For the OSP, we have a feeder fiber and a BSWDM filter at the 1st stage splitting point (1RN) which demultiplexes and multiplexes downstream and upstream signals at a sub-band level, respectively. We have the first distribution fiber to connect the 1RN and the 2nd stage splitting point (2RN) which demultiplexes and multiplexes downstream and upstream signals at a channel level, respectively. Then, we have the second distribution fiber for
connecting customer premises. At the central office (CO), we have mirror image of the OSP except the transmission fibers.

The BSWDM filter used in the proposed architecture consisted of one input and multiple outputs for multiple sub-bands. The transmission characteristics of the BSWDM filter is a sort of coarse wavelength division multiplexing (CWDM) filter based on an AWG [4]. We can also achieve a similar function utilizing a conventional CWDM filter and couplers as discussed in the section 4. The BSWDM filter is realized by cascading two AWGs and can be fabricated in a single chip based on a planar lightwave circuit (PLC) technology. The bandwidth and number of output, i.e., the number of splitting points, are determined by connection configuration between AWGs. Thus, it is possible to maintain low insertion loss independent of the splitting points. Figure 2 depicts a graphical representation of the BSWDM filter and its transmission characteristics. The transmission passband of each output port has wide bandwidth (12.8-nm for our case) and it is periodic with respect to wavelength for every free spectral range (FSR) of the BSWDM filter.

Table 1. Defined parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\lambda_\text{gs}$</td>
<td>Guard band between the sub-bands</td>
</tr>
<tr>
<td>$\lambda_\text{gb}$</td>
<td>Guard band between the super-bands</td>
</tr>
<tr>
<td>$\lambda_c$</td>
<td>Channel spacing</td>
</tr>
<tr>
<td>$m_\text{sb}$</td>
<td>Number of sub-bands that exists within a super-band</td>
</tr>
<tr>
<td>$m$</td>
<td>Integer</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of channels that exists within a sub-band</td>
</tr>
</tbody>
</table>

The wavelength assignment for the proposed multiple star architecture is shown in Fig. 3. For the bidirectional transmission, it has both the upstream (U-band) and downstream (D-bands).
band) super-bands. Then, the super-band is divided into multiple sub-bands. Here, we assumed four sub-bands for both upstream and downstream. The parameters used for a wavelength plan of BSWDM filter are summarized in Table I. The two guard bands, $\lambda_{gb}$ and $\lambda_{gj}$, are needed for separation of two super-bands and separation of multiple sub-bands, respectively. The FSR of an AWG that used for channel multiplexing/demultiplexing at the 2nd stage RN is $\lambda_{gb} + (n-1)\lambda_c$. We also assign the FSR of the BSWDM filter as $\lambda_{gb} + m_{gb}[\lambda_{gj} + (n-1)\lambda_c] - \lambda_{gj}$. Then, to match periodicity of super-band and sub-band, we select the $\lambda_{gb}$ such as $\lambda_{gb} = \lambda_{gj} + m \times (\lambda_{gj} + (n-1) \times \lambda_c)$. By applying this wavelength allocation rule, we can realize a multiple star architecture with a single type AWG at the 2nd RN.

The measured transmission spectra of the 1 x 4 BSWDM filter in both E-band and C-band are shown in Fig. 4 (a) and (b), respectively. The insertion loss of the each passband ranged from 3 to 6 dB. We observed ripples less than 1 dB in the passband. The polarization dependent loss (PDL) at the middle channel of each sub-band has a maximum value of 0.4 dB. This BSWDM filter has bandwidth of 12.8 nm for the passband and guard band of 4.8 nm. The $\lambda_{gj}$ is 40.87 nm with the FSR of 102.4 nm. And, the center wavelengths of each sub-band were 1529.4, 1547, 1564.6, and 1582.2 nm, respectively.

![Fig. 5. Experimental set up for multiple star WDM-PON based on the BSWDM filter (upstream).](image)

![Fig. 6. (a) Measured BER result of 12 WDM channel, (b) locked spectra of upstream data.](image)
3. Experimental setup and results

The experimental setup of the proposed multiple star WDM-PON based on the 1 x 4 BSWDM filter is shown in Fig. 5. The WDM-PON was implemented based on the wavelength-locked Fabry-Perot laser diode (F-P LD) [5]. It may be noted that this architecture can be used independent of the optical sources. The amplified spontaneous emission (ASE) of C-band and L-band generated from 2-stage Erbium-Doped Fiber (EDF) was used as a broadband light source (BLS) for a seed light of the upstream signal. The C-band was used for sub-bands 1 to 3, while L-band was used for sub-band 4. We used a single type AWG with Gaussian passband profile for the CO and the 2nd RNs. The channel spacing and 3-dB bandwidth of the AWG are 100 GHz and 50 GHz, respectively. The BLS output was passing through the feeder fiber, the BSWDM filter, the distribution fiber, and the AWG at the 2nd RN. Then, it was injected into the F-P LD located at the optical network terminations (ONTs). The F-P LD at each ONT was anti-reflection coated and its mode spacing is 0.57-nm. It was directly modulated at 155-Mb/s pseudorandom bit sequence (PRBS) with a length of $2^{31}-1$. The feeder fiber was a single mode fiber (SMF) of 20 km length. The lengths of the distribution fibers were 10 km, 20 km, 10 km, and 0 km, respectively.

For each sub-band, we transmitted 3-channel upstream data to demonstrate feasibility of the proposed architecture. The injected ASE power ranged from -16.7 dBm/0.2 nm to -18.5 dBm/0.2 nm. We measured the bit error rate (BER) for 12 channels after transmission. The measured sensitivity ranged from -37.3 dBm to -36.6 dBm at the BER of $10^{-10}$ as shown in Fig. 6(a). The sensitivity difference can be explained as a result of different injection power and injection position with respect to a lasing mode of the F-P LD. We found that there were no measureable crosstalk induced penalty and dispersion penalty. The measured upstream spectrum of the 12 WDM channels is shown in Fig. 6(b). If we compared the received power and the receiver sensitivity for all channels, we have a margin of 8.8 dB at worst case. However, to increase the transmission length, we need to increase the injection power. This is because the injected BLS has also experienced loss of the transmission fiber. It implies that the transmission length is limited by the available injection power.

The proposed BSWDM filter was designed for 64 channels WDM-PON. In other words, each sub-band can carry 16 channels with 100 GHz spacing, since the passband of the BSWDM filter is 12.8 nm. This was confirmed with total transmission length of 20 km by link budget analysis (injection power analysis) and a single channel transmission at the edge of the each sub-band. In addition, 1 dB ripple in the transmission spectrum of the BSWDM filter does not bring about any penalty.

To verify the feasibility of 1.25 Gb/s transmission per channel, we demonstrated a single channel transmission at sub-band 2. We used an AWG which has a flat-top passband (3 dB bandwidth of 0.61 nm) profile at the CO and 2nd RN. The feeder fiber was maintained as 20
km. However, we reduced the distribution fiber to 5 km to compensate the insertion loss difference between the Gaussian AWG and the flat-top AWG. Then, the injection ASE power into an F-P LD was -16 dBm/0.2 nm. To investigate a color-free ONT, we considered a detuning effect. Here, the detuning is defined as the wavelength difference between the injection ASE and the F-P LD lasing mode, i.e., $\lambda_{ASE} - \lambda_{LD}$. The measured BER curve is shown in Fig. 7 according to detuning value. As seen in BER curves, we observed an error-free transmission regardless of the detuning. Thus, a higher bit rate transmission can be realized to maintain color-free operation of both the OSP and ONT.

4. Discussion

In this paper, we proposed a multiple star architecture utilizing the BSWDM filters. Moreover, this architecture also can be used as a progressively deployable WDM-PON. We can start a deployment of the WDM-PON with only two BSWDM filters. Then, a few subscribers equal to split ratio of the 1st stage can be accommodated. As subscribers are increased, we need to place a single 2nd RN. The rest of the 2nd RN can be additionally installed to accommodate further subscribers. In this manner, we can reduce up-front costs and provide WDM-PON service cost-effectively.

As we mentioned in the section 2, the proposed BSWDM filter can be replaced by a combination of a conventional CWDM filter [6] and 3-dB optical couplers as shown in dotted box in Fig. 8. However, we do not have flexibility on the wavelength plan, since it was fixed by the CWDM band. This becomes an important feature when we use the BLS as a seed light injection. For example, we need a BLS over 73 nm when we keep 1 x 4 splitting ratio with CWDM wavelength band. On the contrary, we need a BLS over 65.6 nm with the proposed BSWDM filter. Further reduction of the BLS bandwidth is possible with more elegant design. Another limitation in the architecture based on CWDM filter is splitting ratio of the 1st RN. It is not easy to have 1st stage splitting ratio more than 4. However, it is very flexible with the proposed BSWDM filter.

In terms of insertion loss of the 1st RN, the BSWDM filter was less than 6 dB over all bands. We are expecting a similar insertion loss for the CWDM filter based case, when we keep 1 x 4 splitting ratio. It may be noted that the insertion loss of the BSWDM filter can be reduced by an improved design and manufacturing process [7]. Furthermore, the cost of the BSWDM filter can be low on account of a single integrated device based on PLC technology.

When the transmission bit rate per channel is 155 Mb/s, the total capacity of the WDM-PON is 10-Gb/s (155.52 Mb/s x 64 ch. = 9.953 Gb/s) for upstream. The total capacity becomes 80-Gb/s (1.25 Gb/s x 64 ch. = 80 Gb/s), when we increase the transmission bit rate to 1.25 Gb/s per channel. In our system, the maximum transmission bit rate can be limited by...
intensity noise of injected ASE source, although there exists the intensity noise suppression in wavelength locking process [8]. It may possible to increase the transmission bit rate to 2.5 Gb/s, when the wavelength of F-P LD mode is matched to that of injection ASE. However, it is not easy to achieve a color-free operation in this case. The further increase of transmission bit rate can be achieved with an injection locking [9].

5. Conclusion

We also experimentally demonstrated a multiple star architecture for WDM-PON which supports a color-free OSP. A periodic transmission characteristic of the AWG and the BSWDM filter enables the color-free operation with a simple wavelength assignment rule. As a result, it simplifies management issues. In addition, the proposed architecture offers pay as you grow feature for small up-front costs.

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