
# Application Note

# Wavelength Selective Switching in Optical Communications

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# 1 Introduction

PowerPhotonic are world leaders in the design and development of microlens arrays for coupling between laser sources, fiber and waveguide arrays, optical multiplexing and optical switching.

Manufactured from synthetic fused silica and using a laser writing process, these microlens arrays are monolithic components designed for high accuracy array collimation and coupling and can be organised in uniform or randomized 1D or 2D arrangements. Please refer to section 5 for more information.

# 2 Wavelength Selective Switching technology

Wavelength Selective Switches (WSS) are commonly used in fibre optical telecommunication networks. In order to meet the ever increasing demand for bandwidth by businesses and consumers, telecom carriers have to increase capacity which is solved by coupling multiple wavelengths into a single fibre. Each wavelength is a separate information channel that needs to be routed through the network in an appropriate manner, and WSS is a key enabling technology for this.

The technology of combining multiple wavelengths into a single optical fibre is called Wavelength Division Multiplexing and is explained schematically in Figure 1. Modern WDM implementations use optical fibres that typically carry around 40 wavelengths spaced at 100GHz or 80 wavelengths spaced at 50GHz, this is called Dense Wavelength Division Multiplexing (DWDM).

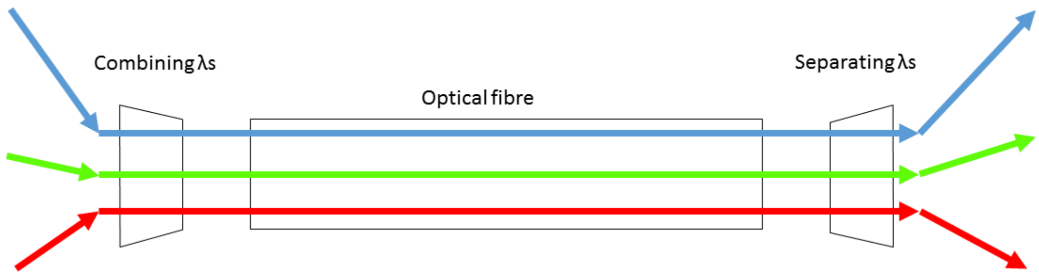


**Figure 1: WDM schematic of operation. 1) Combining the signal into a single optical fibre 2) Transmitting the combined signal within the optical fibre 3) Separating the transferred signals**

An example of a current optical telecommunication network is shown in Figure 2, where multiple wavelengths can be seen traveling throughout the network. At each node specific wavelengths can be dropped, substituted by other wavelengths, or switched from one destination node to another. This allows the operator to reconfigure the network, for instance to re-allocate bandwidth in response to changing demand, or to bring on line a new customer, or to re-route traffic around an equipment or link failure.

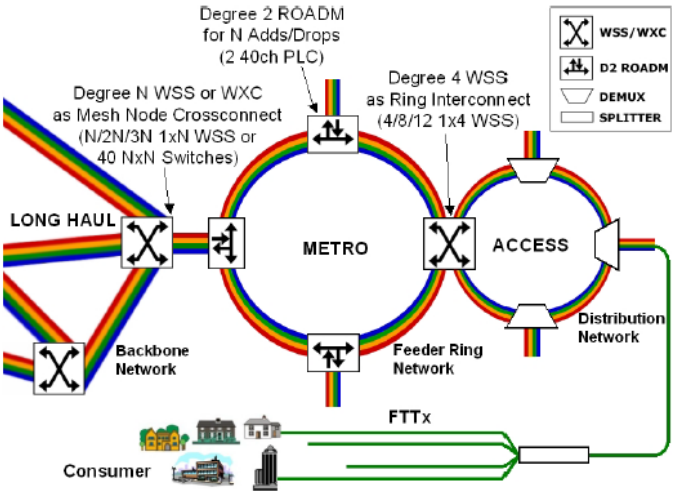


**Figure 2: Typical architecture of a telecom network** [1]

The technology which enables the nodal configurability described above is called Reconfigurable Optical Add Drop Multiplexer (ROADM), in which WSS is a key building block. A major benefit that the WSS technology brings to the current generation of ROADMs is that its ports are 'colourless', meaning that any individual or group of wavelengths from the input port can be allocated to any of the output ports.

## 3 WSS Principle of Operation

WSS technology is based on the principle that the device can separate the incoming light input spectrally as well as spatially, then choose the wavelength that is of interest by deflecting it from the original optical path and then couple it to another optical fibre port, as shown in the Figure 3.

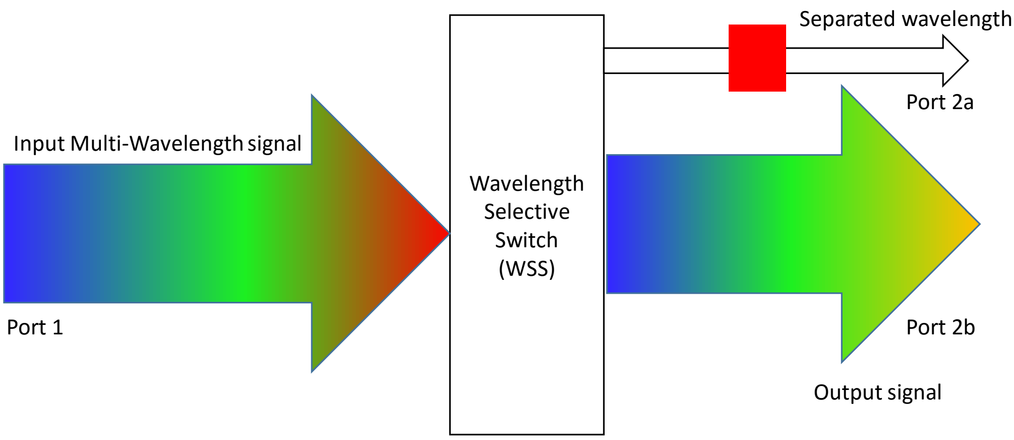


**Figure 3: A diagrammatical representation showing the principle concept behind WSS device operation. A multi-wavelength beam enters the WSS in a common port and the desired wavelengths are selected by the device. The selected wavelengths are then coupled to output optical fibres ports in the desired combination.**

A typical WSS consists of:

a) Fibre array
b) Coupling optics

c) Wavelength separator/combiner
d) Focusing/shaping optics
e) Switching device

A schematic representation of how a WSS work can be seen in Figure 4 which shows a system with 1 input and 2 outputs, known as a 1x2 port switch. The nomenclature for port count used in the telecommunications industry is 1xN, where N is the number of output ports and typical WSS systems include 1x9, 1x20, and 1x23 ports. In the case of Figure 4, an input signal consisting of two wavelengths (red and green) leaves the input port number 1 (a) and enters free space. The free space multi-wavelength beam is collimated by an appropriate lens (b) after which it passes through a wavelength separator/combiner (c). A diffraction grating is most commonly used for this component, which separates the collimated light into individual wavelengths that have different angular components in the “wavelength axis” of the system; the magnitude of the angular separation follows:

$$\theta(\lambda) = \sin^{1}\left(\frac{\lambda}{d}\right) \quad (1)$$

Where θ($\lambda$) is the diffraction angle of each individual signal component with wavelength $\lambda$ after the grating and $d$ is the period of the structures within the grating.

The two diffracted beams are then passed through a set of optics to optimise the beam size and shape for the chosen switching technology; this generally requires the use of high quality micro-optical components (d) in order to minimise insertion losses of the WSS. The reformatted beams propagate to the switching devices, which redirect the beams in the “switch axis” – orthogonal to the wavelength axis – in the direction of the desired output ports. Finally, the beams travel back as shown in Figure 4, reversing the formatting, diffraction and collimation processes, eventually coupling in to output fibre ports 1 and 2. The optical functions that occur in (b) and (d) are both commonly implemented using micro-optic arrays, where the lenslet positions are accurately matched to individual beams.

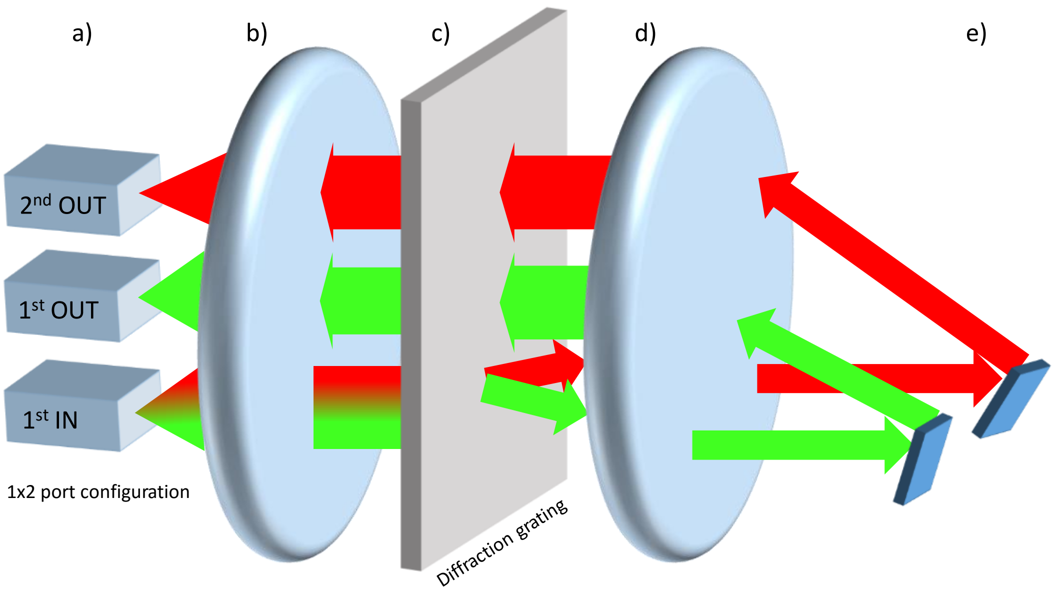


**Figure 4: A figure representing the main components of a 1x2 port WSS switch**

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## 4 Switching devices used in WSS

A number of different technologies can be used as the beam switching devices in a WSS system. The main purpose of each switching solution is to direct the individual input signal channels towards the desired output channel, although they are also sometimes used to attenuate the incoming beam. The main technologies that are used as the switching components in a WSS are described in brief below.

### 4.1 Microelectromechanical Mirrors (MEMS)

A MEMS switch is based on an array of micro-mirrors that move when stimulated by an electrical signal, Figure 5 illustrates the various mirror positions that result in different switch directions. Each individual monochromatic beam (after being split into constituent wavelengths by the diffraction grating) is focused down on to a single micro-mirror which is precisely tilted at the desired angle resulting in an optical path change associated with a particular output channel.

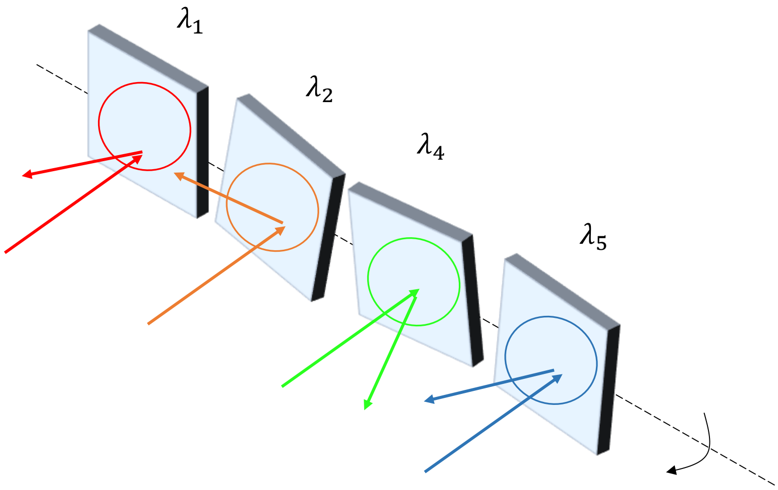



**Figure 5: The principle of operation of a mems based switch, showing 4 different angular output values**

MEMS switches can redirect the incident beam in both the switch axis as well as the wavelength axis, allowing for the minimisation of transient crosstalk; crosstalk being the undesirable coupling of a fraction of one channel in to another, untargeted channel. This effect decreases the signal-to-noise ratio within the channel experiencing crosstalk, but the use of MEMS switches to redirect a beam in two dimensions allows for superior crosstalk attenuation.

### 4.2 Liquid Crystal on Silicon (LCoS)

An LCoS switch changes the direction of an incoming beam by adding a discrete and linear phase shift to the beam wavefront, resulting in an angular redirection of the reflected beam. The incident beam is typically expanded over 10 ~ 100 pixels in order to achieve the desirable switching effect. Figure 6 shows a simplified LCoS switch, where each wavelength is expanded to three cells and different phase shifts are applied that result in different angles of reflection.

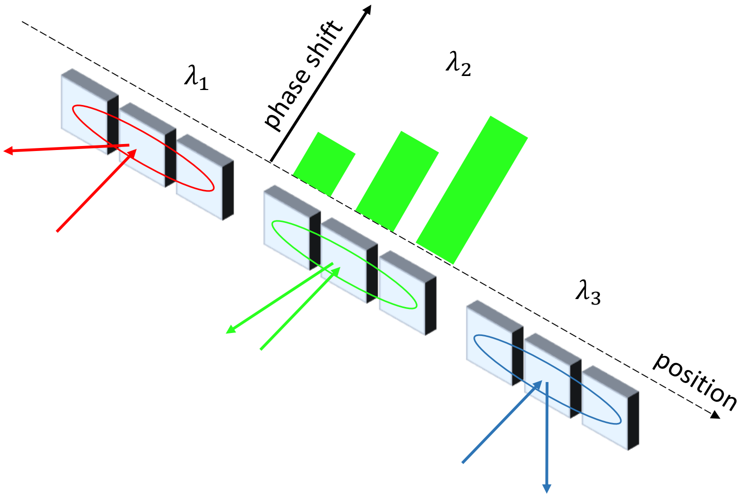



**Figure 6: Principle of operation of a 1x3 port system with 3-pixel LCOS switches**

The main advantage of an LCOS switch is that it does not rely on a moving physical component like the MEMS switch, allowing for potentially faster switching, the disadvantage being that this technology limits the direction and resolution of the switch axis to the number of pixels used for each switch area.

## 5 PowerPhotonic optics for WSS applications

PowerPhotonic specialises in ultra-high precision, custom fused silica micro optics, which is particularly advantageous to the numerous implementations of WSS and other telecommunications applications. The laser machining production process that Powerphotonic uses allows for bespoke and freeform solutions for fibre light coupling to and from a switch, as well as directing and reshaping the beam in a desired fashion. Ultimately this results in the lowest insertion losses, lowest crosstalk and highest coupling performance possible for current and future generation WSS products.

### 5.1 One and two dimensional lens arrays

PowerPhotonic produces both 1- and 2-dimensional lens arrays (Figure 7) for WSS applications, where each lenslet position, pitch, aperture size, RoC and conic constant can be customised to meet the needs of the most demanding telecommunications system.

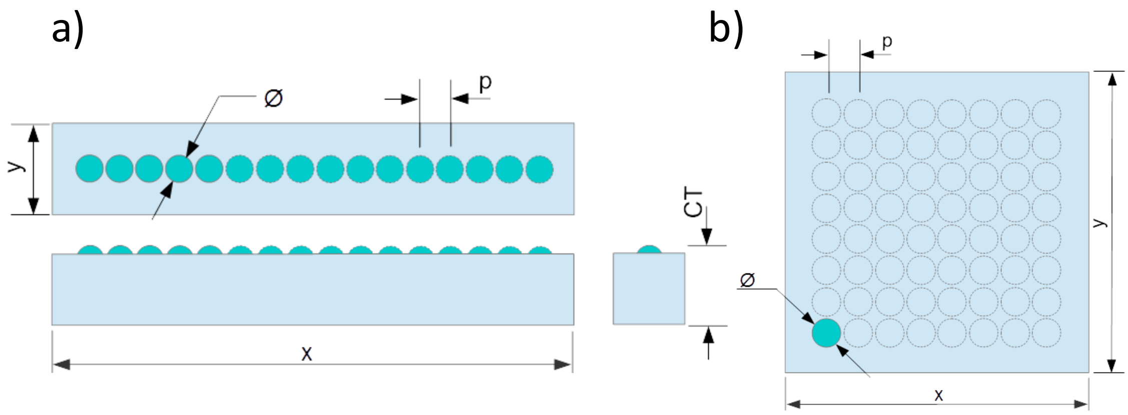
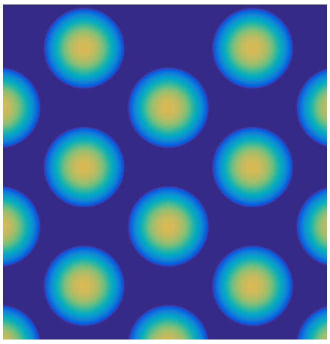



**Figure 7: 1D (a) and 2D (b) micro lens array designs. The various parameters shown in the drawing can be highly customised to meet any application**

## 5.2 Sparse distributed lens arrays

Microlens arrays can be laid out in a sparse distribution for absolute minimisation of crosstalk. Other distributions are also possible and depend on particular application.



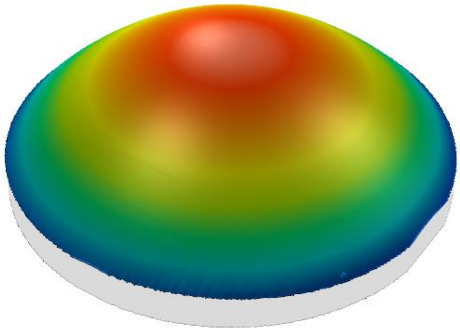


**Figure 8: Custom made micro lens array system. Lenslets are positioned in order to meet the desired optical fibre outputs. White Light Interferometer image of one of the lenslets (right)**

## 5.3 Double sided lenses and arrays with fiducial markings

Double sided lens arrays can be easily produced for higher NA optical fibres with bespoke RoCs and conic constants on both sides of the substrate (Figure 9 a). Fiducial markings can be designed on a substrate for better alignment of the lens in the optical system (Figure 9 b).

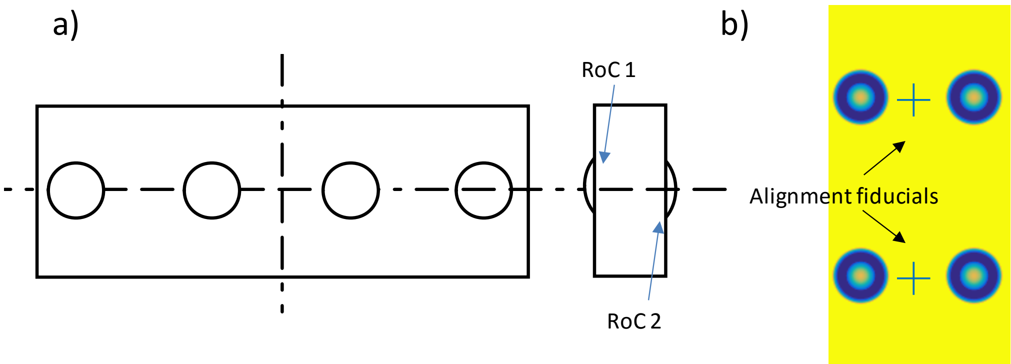



**Figure 9: Design of a double sided lens array (a) with variable RoC. Optical profilometer image (b) of a custom made lens array with fiducial markings engraved for alignment purposes.**

## 5.4 WSS lens arrays designed for long propagation of collimated light

High slope and/or high sagitta (sag) lenses can be designed and manufactured for WSS devices using more demanding regimes such as collimation and propagation of light over longer distances before being coupled back in to a fibre (Figure 10). In these applications each individual lenslet may require a significantly larger clear aperture (CL) than other telecommunications requirements, where the lenses are often 127µm or 250µm in diameter.

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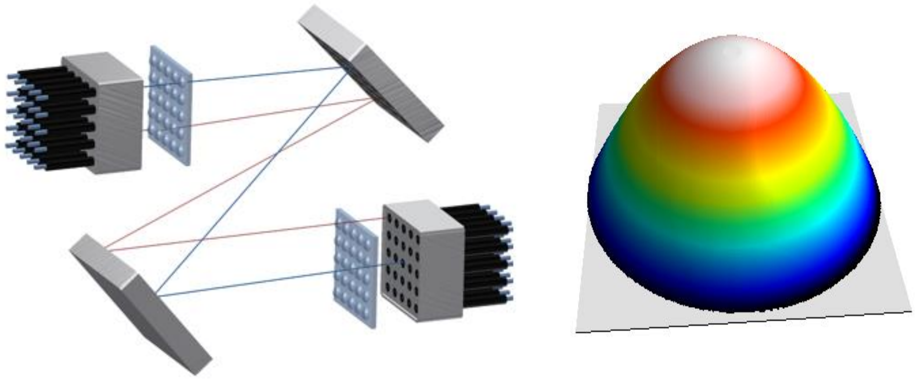

**Figure 10: Free space WSS system with 2D lens arrays designed for long and collimated propagation with a White Light Interferometer image of a lens**

Gaussian beam propagation theory shows that a larger diameter beam will achieve better collimation (i.e. the beam divergence will be lower) than an equivalent beam of smaller beam diameter. Additionally, optimum fibre out- and in-coupling occurs when the fibre facet and beam waist overlap; and when a beam waist is located equidistant between the fibre facets. It follows then that the longer the optical path length is between fibres, the larger the lens aperture needs to be for a given fibre-lens distance. This is described by the following equation:

$$\omega(x)^2 = \omega_0^2\left[1+\left(\frac{\lambda x}{\pi\omega_0^2}\right)^2\right] \tag{2}$$

which calculates a $1/e^2$ Gaussian beam radius $\omega$ at distance $x$ from the beam waist radius $\omega_o$ for a given beam wavelength $\lambda$.

To illustrate, imagine 2 WSS systems that are nominally the same except that the fibre-fibre propagation distance is 10mm for System 1 and 100mm for System 2. In this case let us assume that the switching device requires the beam waist to be coincident with the switch plane (which is equidistant from the fibres) and have a radius of 35µm. Equation 2 shows that System 1 would require a lens with an aperture diameter of at least 236µm in order to capture 99% of the light, similar to other telecommunications requirements, while System 2 would require a lens with aperture diameter of 2117µm. As the lenses are being used with identical fibres they require the same numerical apertures and thus the sag of the lens in System 2 will be significantly higher than that of System 1.

The maximum sag of any given radially symmetric aspherical lens can be calculated as a function of its clear aperture diameter *D*, radius of curvature *R* and conic constant *c* as follows:

$$Sag_{max} = \frac{\left({}^{D}/_{2}\right)^2}{R} * \frac{1}{1+\sqrt{1-\left((1+c)*\frac{\left({}^{D}/_{2}\right)^2}{R^2}\right)}} \tag{3}$$

Using Equation 3, and setting the numerical aperture of both lenslets to 0.14, we find that the maximum sag of the lenslet required for System 1 is 19.3µm while the maximum sag of the lenslet required for System 2 is 174.4µm.

The PowerPhotonic laser fabrication process can be used to produce diffraction limited lenslets with sags up to 200µm, allowing for the manufacture of both Systems described above. This enables the development of new generations of WSS systems that require longer fibre-fibre optical path lengths in order to fit additional components in the beam path such as power monitoring, wavelength monitoring and additional optics.

## 5.5 Lens Quality

Lens arrays produced in Powerphotonic are manufactured using a unique laser processing technology. That leaves the surface of the glass with roughness ($R_q$) of < 1nm. The technology is also beneficial in terms of the accuracy of the manufactured surfaces and their low surface form error, which leads to achieving micro-lenses with insertion losses of less than 0.2 dB.

# 6 Summary

WSS as a part of ROADM systems are becoming increasingly popular within the telecom industry, mainly due to their extremely low insertion losses coupled with their high level of flexibility. Both MEMS and LCoS technologies are used as the fundamental switch technologies, with each having their own set of advantages and lensing requirements. In order for these switches to function properly they must be used with appropriately designed and manufactured micro-optical components. These optics, which are usually in a form of a micro-lens arrays, control the beam shape, direction, divergence and quality and should be designed to meet the particular demands of the chosen switching technology.

In this rapidly changing market, where new WSS configurations need to be technologically addressed, bespoke optical elements are required more often. PowerPhotonic has proved to manufacture robust and customised optics with the highest optical surface quality that enables optimal lens performance. Our fused silica laser manufacturing technology is a great tool for customised and freeform solutions.

For more information, visit powerphotonic.com or contact us:

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# 7 References

1. Eldada L. 'ROADM Architectures and Technologies for Agile Optical Networks'

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