Arrayed-waveguide grating lasers and their applications to tuning-free wavelength routing

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Indexing terms: Waveguide lasers, Multiplexing, Ring lasers, Fabry–Perot lasers

Abstract: The authors propose two kinds of tunable arrayed-waveguide grating (AWG) lasers. One is an AWG ring laser using an AWG multiplexer and an erbium-doped fibre amplifier (EDFA). The other is an AWG Fabry–Perot laser constructed using an AWG multiplexer with the minimum number of inputs/outputs and laser diode (LD) amplifiers; fewer than the desired number of wavelengths. These fabricated 1.55µm tunable AWG lasers are shown to oscillate successfully at 16 and 32 wavelengths with a 0.8 nm wavelength spacing. As the useful application of the tunable AWG laser source for dense wavelength division multiplexing (WDM) networks, a new lightwave transrouter (LTR) is constructed using the AWG multiplexer formed of an appropriate pair of a fibre ring laser and a wavelength router. The LTR can successfully route a lightwave signal to a desired wavelength-addressed channel. The fabricated 1.55µm 15-channel tunable LTR is routed automatically to the corresponding channel. The unique configuration is particularly attractive because of the principle tuning-free mechanism. Additionally, a reflective modulator is introduced into a sourceless optical network unit (ONU) for WDM passive optical networks (PONs) and then its fine-signal response is obtained.

1 Introduction

Dense wavelength division multiplexing (WDM) networks are very attractive as a result of the development of arrayed-waveguide grating (AWG) [1] $N \times N$ multiplexers [2, 3]. The AWG add-drop multiplexer [4] and the channel selection filter [5–7] were proposed as new applications in dense WDM ring networks [8–11]. This AWG multiplexer device plays an important role in WDM networks because of its unique N input and N output geometry. A conventional AWG tunable laser [12, 13] requires at least N input/output ports and N amplifiers to oscillate N wavelengths. It is particularly important with this laser to obtain good suppression of amplified spontaneous emission (ASE) and output power flatness at every wavelength. These significant problems are solved by using the proposed tunable AWG laser shown in Fig. 1. By introducing a special device arrangement, the minimum number of amplifiers and of input/output ports in the multiplexer, fewer than N, are sufficient to oscillate N different wavelengths.

Silica–glass based [14] AWG multiplexers are also expected to be used as key devices for other applications in dense WDM networks with star topologies. The conventional wavelength routing system consists of a tunable laser and a 1 × N multiplexer. The laser must be more accurately tuned to the multiplexer so that they have identical wavelengths. This significant tuning problem is solved by using the proposed transrouter [15] shown in Fig. 2. As only one $N \times N$ multiplexer is employed, the lasing wavelength can be tuned automatically to the demultiplexing wavelength.

This paper describes novel tunable AWG lasers based on the appropriate combination of a single AWG multiplexer and optical amplifiers and their successful demonstrations with a view to applying them in the construction of dense WDM networks. We also describe a novel transrouter, based on a single polarisation-insensitive [16] AWG multiplexer with an available function as a transmitter/router, for constructing wavelength-addressed star networks or WDM passive optical networks (PONs) [17]. We first introduce design concepts and configurations of two types of tunable AWG lasers

(*a*) AWG ring laser

(*b*) AWG Fabry–Perot (F–P) laser.

Next, attractive operation principles of these fabricated AWG lasers and their successful demonstration results are exhibited in detail. Finally, a tuning-free AWG transrouter configuration is proposed and its successful demonstration is accomplished, as one of useful applications. Consequently, it is confirmed that these AWG components operate in accordance with the design.

2 AWG laser configurations and experimental results

We describe here the design and performance of two kinds of proposed tunable lasers, the AWG ring laser and the AWG F–P laser.

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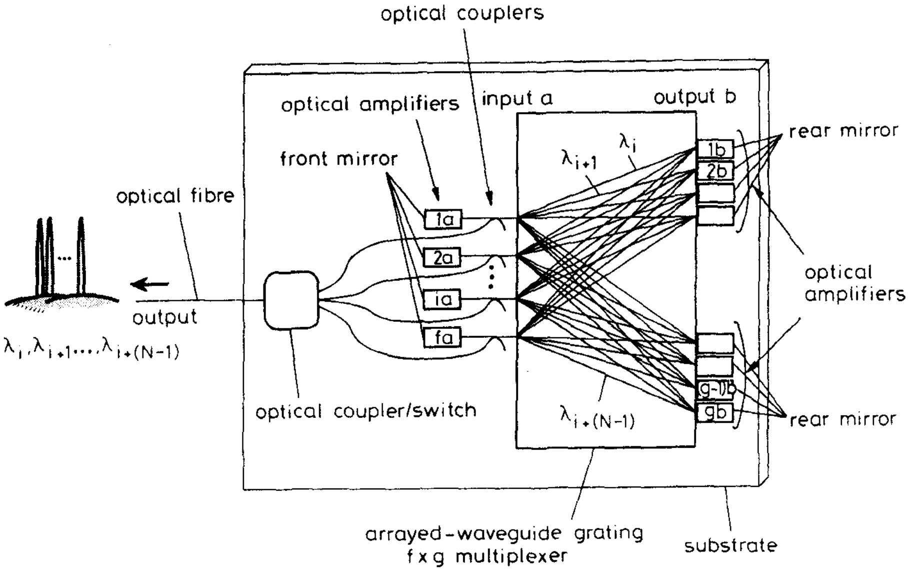

Fig. 1 *Proposed N-wavelength tunable AWG F–P laser configuration*

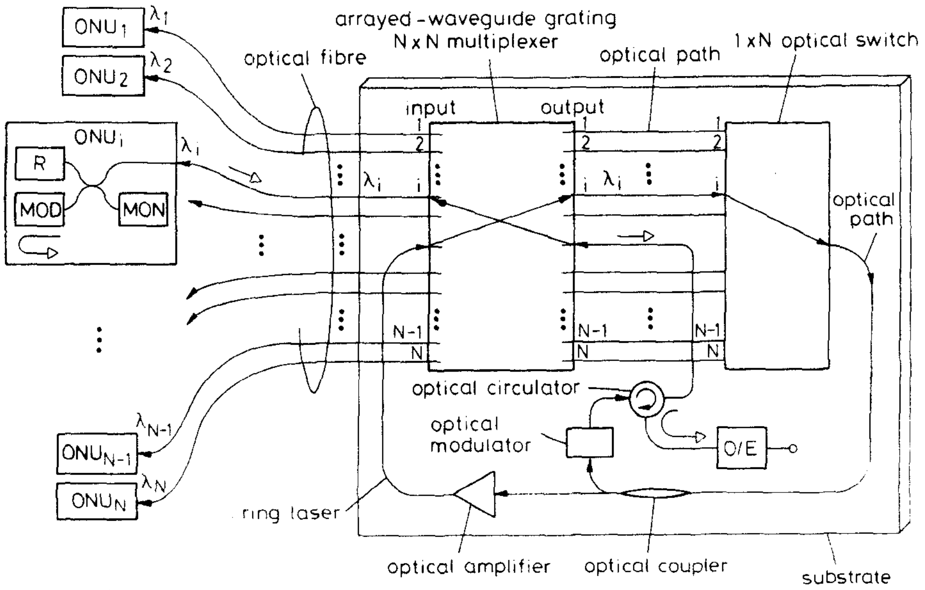

Fig. 2 *Lightwave transrouter configuration*

2.1 Tunable AWG ring laser

Fig. 3 shows the proposed tunable AWG ring laser configuration. The novel tunable AWG ring laser, which consists of a ring laser and an optical switch, is based on available use of a single AWG $N \times N$ multiplexer. One input port of the tunable AWG ring laser is reserved as a common input port. The AWG ring laser is first operated at λ_i, a single wavelength of the AWG multiplexer in output port #i selected by a 1 × N switch. In a similar way, another desired wavelength λ_{i+1} can be oscillated by selecting its corresponding output port # $i + 1$. Finally, any desired one of N wavelengths is operated and fed into one output port of an optical coupler. There are distinguished features such as a same-wavelength spacing and a stable oscillating wavelength. This is because intrinsic merits of a silica–glass based AWG device are provided.

To confirm the operation of the proposed AWG ring laser, a 16-channel operative AWG ring laser is illustrated in Fig. 4. It is based on a silica–glass based 1.55μm AWG 16 × 16 multiplexer with a 0.8nm wavelength spacing. The polarisation-insensitive [16] AWG was fabricated on a silicon substrate using silica-based planar lightwave circuit technologies [14]. The multiplexer chip was 30mm × 40mm. The fibre ring laser was constructed by incorporating a 1480nm LD-pumped EDFA, a 16 × 16 AWG multiplexer, 1 × 2 latching-type fibre switches [18] and a 2 × 2 fibre coupler. Port 9*a* in the multiplexer was assigned as the common input port.

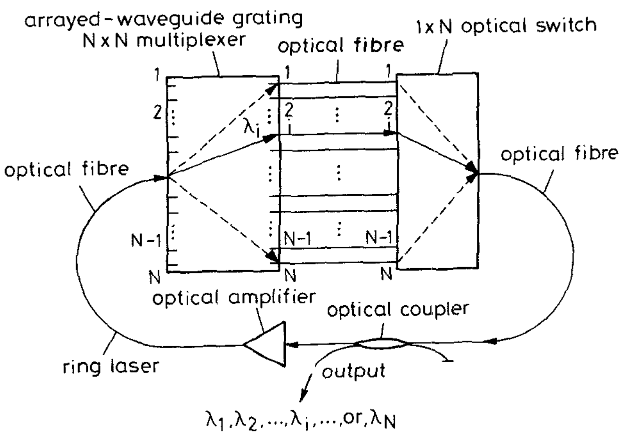

Fig. 3 *Proposed tunable AWG ring laser configuration*

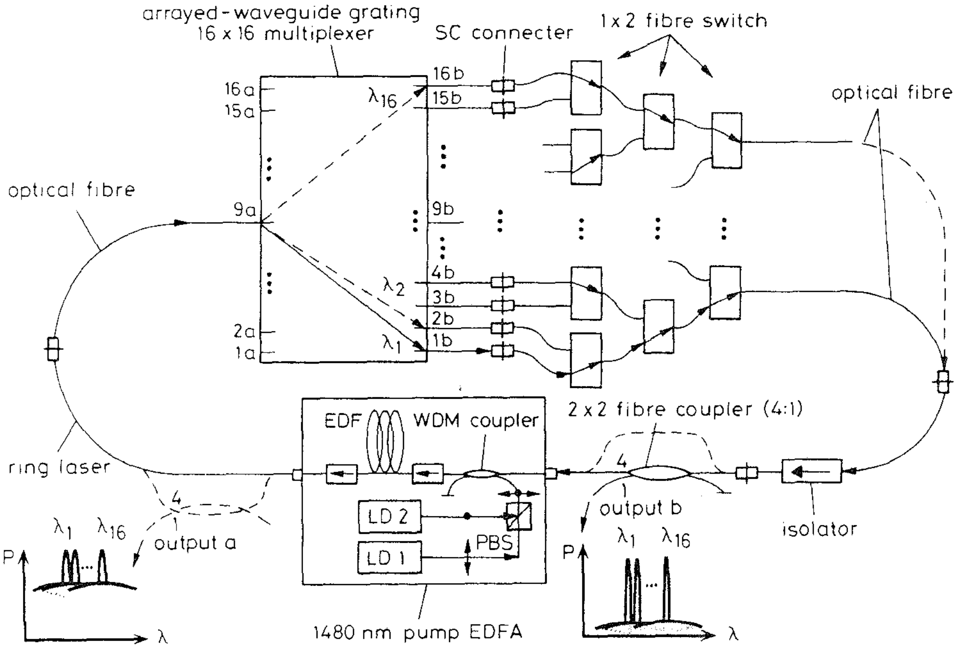

Fig. 4 *Setup for tunable AWG ring laser demonstration*

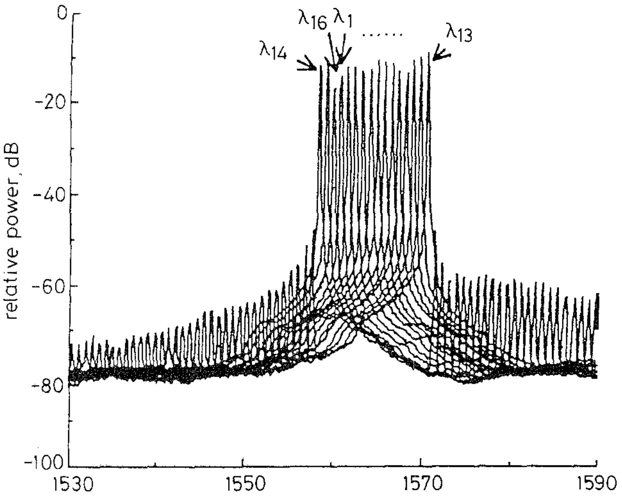

Fig. 5 *Lasing spectra in tunable AWG ring laser 16-wavelength lasing spectra*

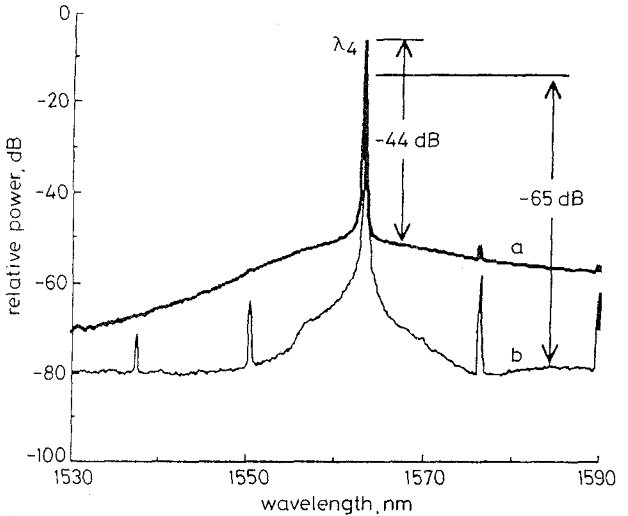

Fig. 6 *Lasing spectra in tunable AWG ring laser*
Suppression effect of ASE (*a*) without ASE suppression, (*b*) with ASE suppression

Fig. 5 shows the measured lasing spectra for the fabricated ring laser when the assigned wavelengths in the AWG output ports are selected by optical switches.

The step-wise tunable lasing spectra are characterised by 16 lasing peaks with a 0.8nm wavelength spacing, corresponding to an optical-frequency separation of 100GHz. The wavelength at which lasing was possible depended on the grating order of the AWG and the gain distribution of the EDFA. In the transrouter case, as described in Section 2.3, the transmission path in the AWG corresponding to λ_9 could not be used. This is because this channel is occupied by the common output port and so there is no ring laser path for this wavelength. A high side-mode suppression ratio of –35 to –45dB was achieved. Fig. 6 displays the suppression effect of the amplified spontaneous emission (ASE), comparing the two cases (*a*) without ASE suppression and (*b*) with ASE suppression. Both cases mean that there is a difference between two output ports in inserting a coupler. The high signal-to-ASE ratio of about –65dB was accomplished, as shown by the lasing spectrum (*b*) in Fig. 6, which was much lower than –44dB of the lasing spectrum (*a*). This is because the unwanted ASE light was sufficiently reduced by taking out directly the filtered output from the AWG multiplexer. Whereas, the output power in the case (*a*) was higher than that of the case (*b*), because of no filtering. The I–L curves in the case (*a*) were shown for single pumping and double pumping in Fig. 7. As a result, high output power of up to 1mW (= 0dBm) was obtained at 500mA above the threshold of 230mA when the EDFA was pumped in orthogonal modes by using two LDs. Even in the case (*b*), therefore, higher output power can be obtained by such stronger LD pumping.

2.2 Smart tunable AWG Fabry–Perot laser

Fig. 1 shows the configuration of another *N*-wavelength tunable integrated-optic AWG F–P laser. This AWG F–P laser was constructed using an AWG multiplexer with the minimum number of inputs/outputs and optical amplifiers; fewer than the desired number of wavelengths. Thus, this laser consists of a $f \times g$ AWG multiplexer with f input/g output ports and $(f + g)$ optical amplifiers, when $N = f \times g$. Combinations between specified input and output ports in the AWG multiplexer are reserved as *N* possible wavelength channels. The AWG laser is first oscillated at λ_i, a single wavelength of the AWG multiplexer selected by a pair of input/output amplifiers #1*a* and #1*b*, and the lasing output is fed into one output port of an optical coupler or switch. Then, the AWG laser oscillates at the centre wavelength of the corresponding passband in the AWG multiplexer. In a similar way, another desired wavelength λ_{i+1} can be oscillated by selecting its corresponding input/output port #1*a* and #2*b* pair. Finally, a $\lambda_{i+(N-1)}$ wavelength can be oscillated by selecting combinations of ports #*fa* and #*gb*. Consequently, as many as *N* optical wavelengths can be operated.

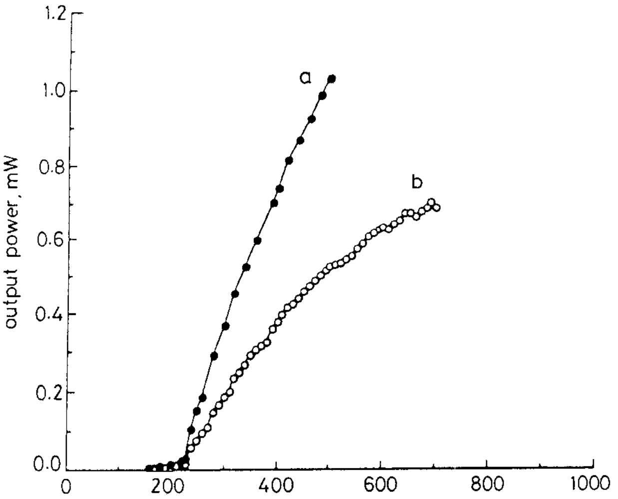

Fig. 7 *Lasing spectra in tunable AWG ring laser*
I-L characteristics of the AWG ring laser (*a*) single LD pumping, (*b*) double LD pumping

We constructed the 32-wavelength tunable AWG F–P laser shown in Fig. 8 to confirm its operation. It main component is a silica-glass based 1.55µm AWG 32 × 32 multiplexer with a 0.8nm wavelength spacing. The AWG multiplexer was fabricated on a silicon substrate using silica-based planar lightwave circuit technologies [14]. The multiplexer chip size was 30 × 40mm^2. The AWG laser was constructed using a 1.55µm LD amplifier, a 32 × 32 AWG multiplexer, 1 × 4 latching-type fibre switches [10], and a 2 × 2 fibre coupler (with a power splitting ratio of 1:4). Ports {11*a*, 15*a*, 19*a*, 23*a*} and ports {7*b*, 8*b*, 9*b*, 10*b*, 23*b*, 24*b*, 25*b*, 26*b*} in the multiplexer were assigned as four input and eight output ports, respectively. A pair of dielectric multilayer coated film mirrors were used on the LD amplifier output and the multiplexer output ports to construct a Fabry–Perot cavity.

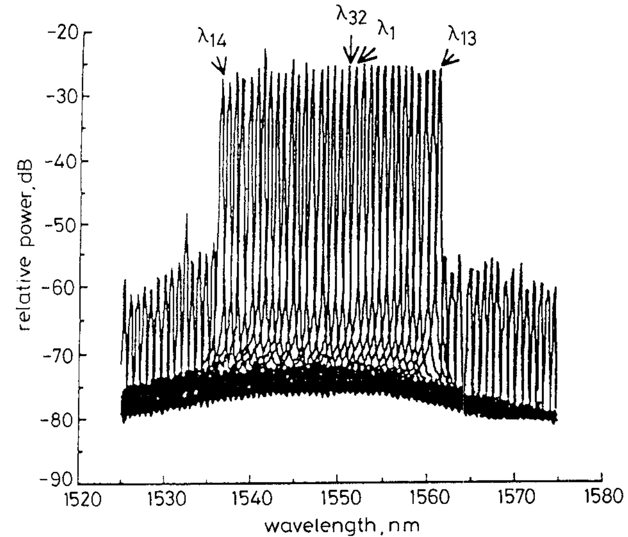

Fig. 9 *Lasing spectra of the tunable AWG F–P laser*
32-wavelength lasing spectra of a tunable AWG F–P laser

Fig. 9 shows the measured lasing spectra for the fabricated AWG F–P laser when the assigned wavelengths in the AWG input/output ports are selected by 1 × 4 switches. The stepwise tunable lasing spectra are characterised by 32 lasing peaks with a 0.8nm (= 100GHz) wavelength spacing. The wavelength at which lasing was possible depended on the grating order of the AWG and the gain distribution of the LD amplifier. The LD amplifier was operated with a gain of 15dB at injection current of 75mA. The net gain of this laser was then estimated to be around 3dB for the AWG and the coupler losses. A high ASE suppression ratio of –50dB was achieved at one output port '*a*' with ASE filtering, which was less than that of –30dB at another output port '*b*' without ASE filtering as shown in Fig. 10. This is because the filtered output was obtained directly from the AWG multiplexer by using the 2 × 2 fibre coupler (with a splitting ratio of 4:1). The lasing spectrum has side modes corresponding

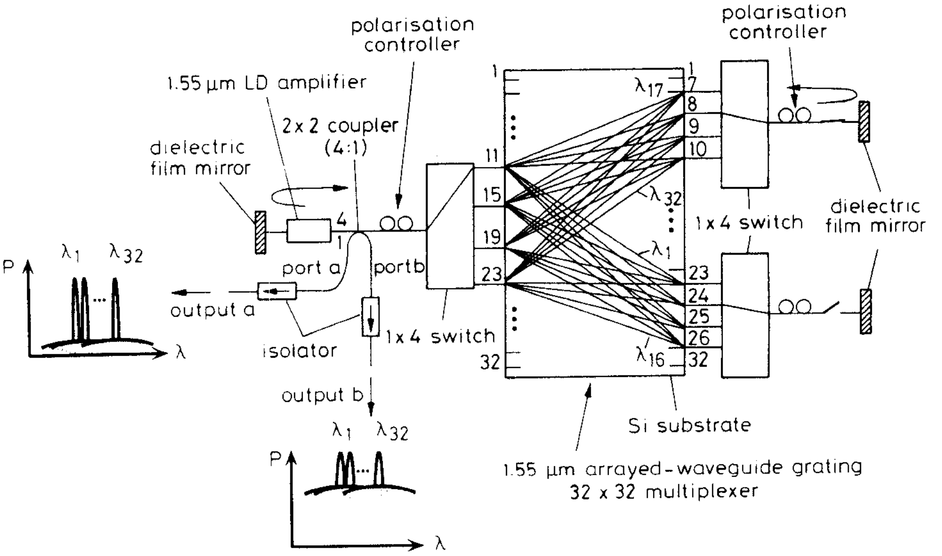

Fig. 8 *Setup for 32-wavelength tunable AWG F–P laser*

to the free spectral range (the grating order) of a 25.6nm spacing. Undesired mode oscillation due to the adjacent grating order can be greatly suppressed by introducing a bandpass filter into the laser output port [15]. In principle, this long external Fabry–Perot cavity structure allows many longitudinal modes to lie within the AWG multiplexer pass bandwidth. Our spectrum measurement was limited to a 0.1nm resolution of the spectrum analyser. Multilongitudinal mode oscillation could be probably displayed at a high-resolution scanning filter. The I–L curves were shown by curve '*a*' at the low ASE port *a* and by curve '*b*' at the high power port *b* in Fig. 11. As a result, output power of up to 0.27mW in the high power port '*b*' and 0.005mW in the low ASE port '*a*' were obtained at 100mA above the threshold of 45mA. The output power was relatively low because only one LD amplifier was used. That is to say, the gain is not sufficiently large to contribute the stimulated emission. In the case '*a*', therefore, higher output power will be obtained under higher gain conditions using a pair of LD amplifiers.

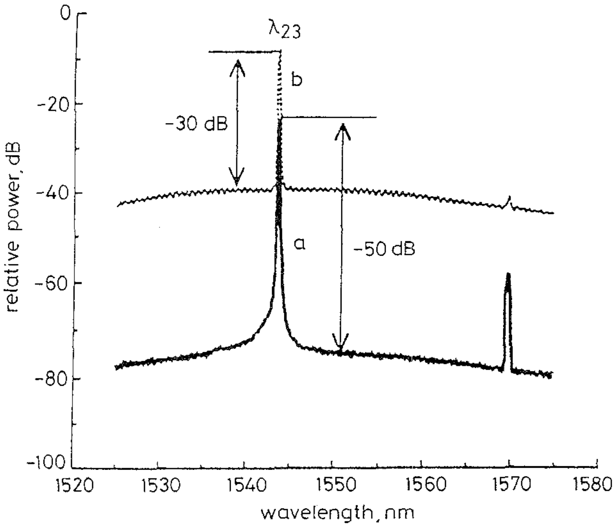

Fig. 10 *Lasing spectra of the tunable AWG F–P laser*
Typical lasing spectrum λ_{23} (*a*) with ASE filtering at one output port, (*b*) without ASE filtering at another output port

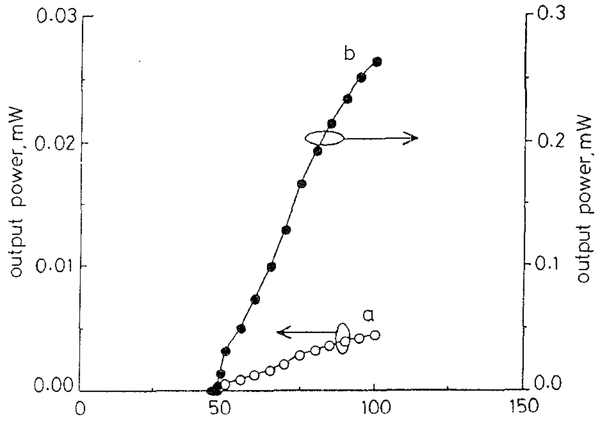

Fig. 11 *Lasing spectra of the tunable AWG F–P laser*
I–L characteristics of the AWG F–P laser (*a*) at one output port a with ASE suppression, (*b*) at another output port b without ASE suppression

3 Application to tuning-free lightwave transrouter

Fig. 2 shows the proposed lightwave transrouter (LTR) [15] configuration. The novel LTR which consists of a transmitter (ring laser) and a wavelength router is based on their common use in a single AWG $N \times N$ multiplexer. One input port of the ring laser and one output port of the router are reserved as common input and output ports. The ring laser is first operated at λ_i, a single wavelength of the grating multiplexer selected by a $1 \times N$ switch, and one of $N - 1$ output signals is fed into the common output port. Then, the lasing wavelength automatically matches the corresponding centre wavelength of the AWG. This is because of the symmetric structure of the AWG $N \times N$ multiplexer with N input ports and N output ports. A desired wavelength can be delivered by selecting its corresponding output port. As many as $N - 1$ optical wavelength channels can be routed by switching at other wavelengths.

To confirm the operation of the proposed transrouter, a 15-channel operative LTR is illustrated in Fig. 12. It is based on a silica–glass based AWG 16 × 16 multiplexer with a 0.8 nm wavelength spacing. Ports 9*a* and 9*b* in the multiplexer were assigned as common input and output ports. In this case, the transmission path in the AWG corresponding to λ_9 could not be used. This is because this channel is occupied by common input and output ports and so there is no ring laser path for this wavelength. Fig. 13 shows the lasing spectrum in the transrouter and the wavelength response of the AWG. It can be seen that symmetric paths 9*a*-1*b* and 1*a*-9*b* have the same wavelength response. These spectra mean that the lasing wavelength λ_1 exactly matched the passband wavelength in the *n*th grating order. The lasing spectrum exhibits side modes corresponding to the free spectral range (the other grating order) of a 12.8nm spacing. When the switch was turned on, fine wavelength routing was achieved as shown typically in the λ_4 (9*b*-4*a* path) and λ_8 (9*b*-8*a* path) channels in Fig. 14. Undesired mode oscillation due to the adjacent grating order was greatly suppressed by introducing a bandpass filter into the ring laser output, as shown in Fig. 14. As a result, the side mode was suppressed to less than –65dB. If a more advanced transrouter is used, multiwavelength routing will be possible.

We consider here the application of the AWG ring laser to WDM PONs [17]. We introduce a reflective modulator as a transmitter into 'optical sourceless ONUs' for bidirectional WDM PONs. The signal transmitter was constructed by a 1 × 2 latching type fibre switch/modulator with a dielectric mirror and a 2 × 2 fibre coupler. The optical signal transmitting in the ONU is made by modulating the continuous wave (cw) laser light propagated through a single-mode fibre from the transrouter. The modulated signal was returned to the transrouter and then detected by using a pin-PD and a preamplifier. Figs. 15–17 shows the signal responses of the reflective modulator. The modulated signal to the 1 × 2 fibre switch is displayed by the trace in Fig. 15. The bipolar voltage pulse was supplied for the fibre switch to modulate the received cw light intensity. The light output response time was less than 1ms. The traces in Figs. 16 and 17 show fine optical signal responses at the monitor port of the modulater and the detection port of the transrouter. The phase condition between both pulse waveforms was different by 180°. This is because both output ports were exchanged by switching on/off.

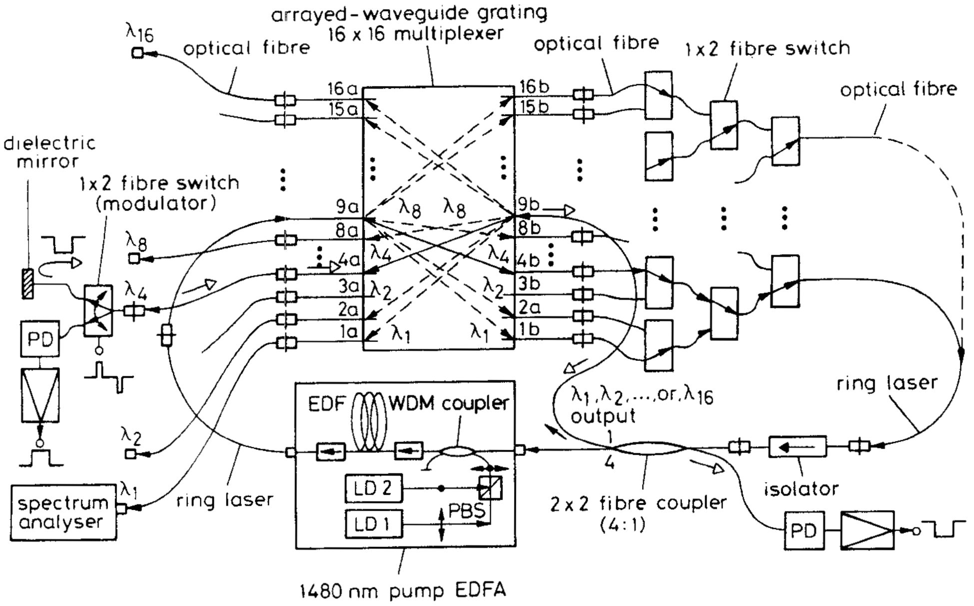

Fig. 12 *Setup for transrouter demonstration*

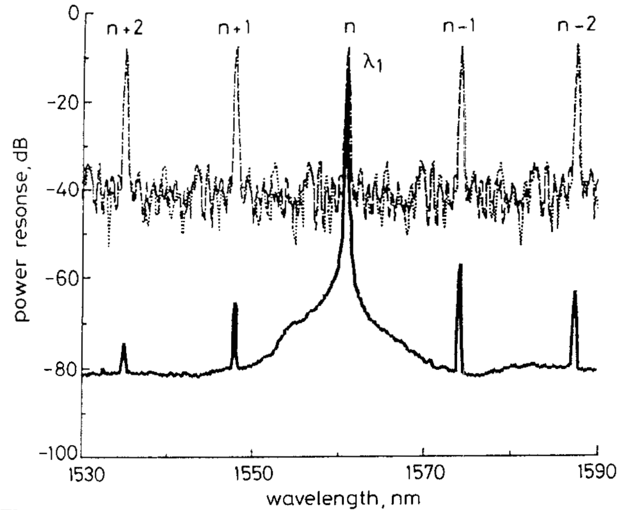

Fig. 13 *Lasing spectra and spectral responses*
Lasing spectrum in transrouter and wavelength response of AWG multiplexer
——— lasing spectrum at λ_1
–·–·– 9*a*-1*b* path
········ 1*a*-9*b* path

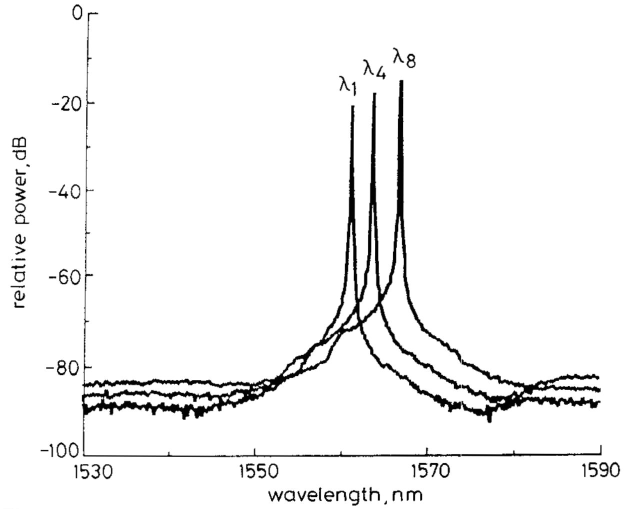

Fig. 14 *Lasing spectra and spectral responses*
Typical wavelength-routed spectra switched on in transrouter

4 Conclusions

We proposed two types of novel tunable AWG laser configurations and demonstrated them successfully. In the AWG ring laser, the stepwise tunable lasing was first accomplished at 16 wavelengths with a 0.8nm spacing. A high side-mode suppression ratio of –35 to –45dB was achieved. A high ASE suppression ratio of

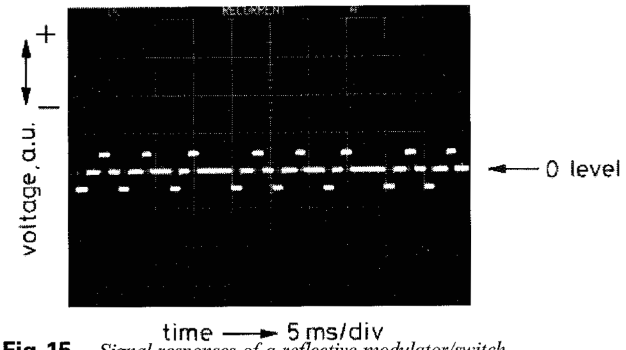

Fig. 15 *Signal responses of a reflective modulator/switch*
Modulated signal to modulator

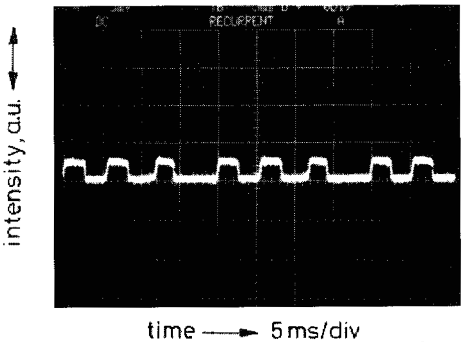

Fig. 16 *Signal responses of a reflective modulator/switch*
Monitored signal in modulator

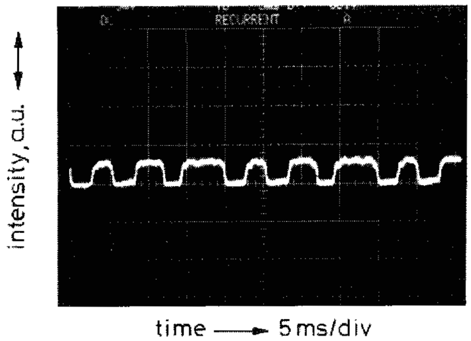

Fig. 17 *Signal responses of a reflective modulator/switch*
Detected signal in transrouter

–65dB was obtained with ASE filtering which was less than that of –44dB without ASE filtering. In the high ASE case, power of up to 1mW was then obtained by higher power pumping. Next, we confirmed that tunable 32-wavelength lasing with a 0.8nm spacing was accomplished using a single AWG multiplexer with the minimum number of inputs/outputs and an optical amplifier. A high ASE suppression ratio of –50dB was achieved with ASE filtering which was less than that of –30dB at another output port without ASE filtering. Finally, we proposed a novel lightwave transrouter and undertook a successful demonstration experiment, as one of useful applications of AWG lasers. Consequently, it was confirmed that the lasing wavelength was matched automatically with the routing wavelength. Additionally, fine-signal response was achieved by using a latching type switch, as a reflective modulator for a sourceless ONU in WDM PONs.

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