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# Low-cost OCDMA Encoding Device based on Arrayed Waveguide Gratings (AWGs) and Optical Switches

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## 1. Introduction

The development of optical fiber communication in the last few years has made the optical fiber as a strong candidate for the future of telecommunication system. Optical code division multiple access (OCDMA) is one of the promising techniques for next generation broadband access network with unique features of full asynchronous transmission, low latency access, soft capacity on demand as well as optical layer security. The successful of CDMA has motivated the telecommunication community to investigate the potential of CDMA in optical domain. In OCDMA system, signals are encoded and decoded in optical domain without converting into electronic. There are many different kinds of OCDMA encoder and decoder, including coherent time-spreading (TS), Optical Orthogonal Code (OOC), Fiber Bragg Grating (FBG), Arrayed Waveguide Grating (AWG), and etc.

AWG is one of the most promising devices for de(multiplexer) in optical communication systems due to the fact that AWG device have been proven capable of precisely de(multiplexing) a high number of optical signals with low insertion loss, high stability and low cost. This paper described the design and development of a low-cost encoding device for OCDMA systems based on AWG devices and optical switches, which is one of the new technologies of data transmission as compared to the conventional system. The OCDMA encoder is used to transmit the coded data in the optical communication system by using a 16-channels AWG device and optical switches. This device promised a high security for data transmission because all the data will be transmitted in code form. The output wavelength from an AWG is coded with the binary code that are given by optical switch before that signal modulate with the carrier and transmitted to the receiver. An integrated circuit (IC) 7805 voltage regulator circuit is designed to supply direct current (DC) at 5 volt for the optical switches. The N-ports encoder used N double pole double throw (DPDT) toggle switches to control the polarization of voltage source from +5 V to -5 V for 16 optical switches. When +5 V is given, the optical switch will give code '1' and vice versa.

In a proper design, an AWG device is specified by the number of channels, center frequency ( $f_c$ ), channel spacing ( $\Delta f_{ch}$ ), free spectral range ( $\Delta f_{FSR}$ ), channel bandwidth, maximum

insertion loss, maximum non-uniformity, maximum crosstalk level, and polarization dependence. Issues affecting the performance of AWG device including crosstalk, insertion loss (IL), polarization dependent dispersion, polarization rotation, passband shape, and passband position are discussed in this paper. Two methods are being used to study the specifications and characteristics of the AWG-based OCDMA encoder: linearity test and continuous signal test. Broadband source, tunable light source (TLS), and optical spectrum analyzer (OSA) are the measurement instruments that used to characterize the encoding device prototype to get the linearity of AWG, insertion loss, optical signal-noise-ratio (OSNR), insertion loss uniformity (non-uniformity), and crosstalk. The experimental results showed the crosstalk, insertion loss, insertion loss uniformity, and OSNR are 9.77 dB, <12 dB, <1.63dB, and  $\geq 20$  dB.

One of the applications of AWG-based OCDMA encoder is optical communication on passive optical networks (PONs). OCDMA has a powerful natural fit on PON because both are based on broadcast-and-select. As such, optimal sharing of optical medium and carrier is obtained. A PON shared-fiber architecture is envisaged to provide optical transparency in the access network layer, or even beyond. Using OCDMA on multiple wavelength channels in a PON offers huge bandwidths to a large number of subscribers for reduced infrastructure costs.

## 2. Arrayed Waveguide Grating (AWG)

In recent years, AWG has become increasingly popular as wavelength de(multiplexer) for wavelength division multiplexing (WDM) applications. They have proven to be capable of precise demultiplexing of a large number of channels with relative low losses (Amersfoort, 1998). AWG was first proposed as a solution to the WDM problem by Smit in 1988 and was further developed in the following years by Takahashi (1990) who reported the first devices operating in the long wavelength window. Dragone (1991) extended the concept from 1xN demultiplexers to NxN wavelength routers which play an important role in multi-wavelength network application.

AWG also known as phased-array based device (PHASAR), because an array of waveguides is used for the de(multiplexing) of optical signals carrying transmission data with various wavelengths. The differences in length between the arrayed waveguides are critical for the necessary focusing and dispersion (whereby the signals are focused into the different output waveguides according to their wavelength).

The key advantage of the AWG is that its cost is not dependent on wavelength count as in the dielectric filter solution. Therefore it suits metropolitan applications that require the cost-effective of large wavelength counts. Other advantage of the AWG is the flexibility of selecting its channel number and channel spacing and, as a result, various kinds of AWG's can be fabricated in a similar manner (Shaari & Kien, 2000).

### 2.1 Operation Principles of AWG

Figure 1 illustrated a schematic layout of an AWG demultiplexer. The device consists of three main parts, which are input and output waveguides, two slab waveguide star couplers or free propagation region (FPR), and a phased array of multiple channel waveguides having a constant optical path length difference between adjacent waveguides (Adam et al., 2008). The operation principle of the AWG de(multiplexer) is described as follows:

In the conventional AWG, the incoming lightwave (DWDM/CWDM signal) propagates into the slab waveguide of the star coupler and diverges. It then propagates to the input aperture of array waveguides and is collected by, and propagates independently into, each arm of the array. The length of the array waveguides has been designed such that the optical path length difference ( $\Delta L$ ) between adjacent array waveguides equals an integer ( $m$ ) multiple of the center wavelength ( $\lambda_c$ ) of the demultiplexer. As a consequence, the field distribution at the input aperture will be reproduced at the output aperture. Therefore, at this center wavelength, the light focuses in the center of the image plane (provided that the input waveguide is centered in the input plane) (Amersfoort, 1998).

If the input wavelength is detuned from this center wavelength, phase changes occur in the array branches. Due to the constant path length difference between adjacent waveguides, this phase change increases linearly from the inner to outer array waveguides, which causes the wave front to be tilted at the output aperture. Consequently, the focal point in the image plane is shifted away from the center (Driessen et al., 2004). By placing receiver waveguides at proper positions along the image plane, spatial separation of the different wavelength channels is obtained.

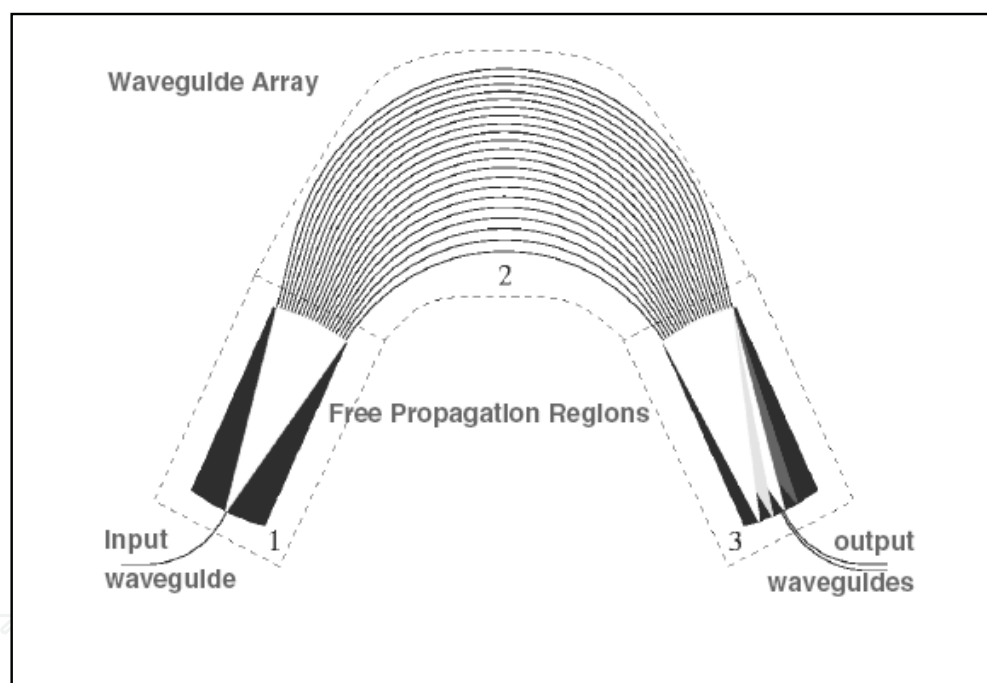


Fig. 1. The structure of AWG demultiplexer (Adam et al., 2008)

## 2.2 Principles of Coding in Optical Domain

Encoder and decoder are a pair of devices or subsystems required in an OCDMA system, where the encoder is at the transmitter and decoder is at the receiver. The function of the encoder is to amplitude-spectrally encode the source according to the specific code it uses. One unique encoded spectrum represents one channel; while a decoder consists of filter arranged in unique configurations with other components. Encoder and decoder can be implemented using any types of optical filtering technology, including AWGs, FBGs, free-space diffraction gratings, thin-film filters and etc (Al-Junid et al., 2008).

### 2.3 Issues Affecting The Performance of AWGs

In a proper design, an AWG device is specified by the number of channels, center frequency ( $f_c$ ), and channel spacing ( $\Delta f_{ch}$ ), free spectral range ( $\Delta f_{FSR}$ ), channel bandwidth, maximum insertion loss, maximum non-uniformity, maximum crosstalk level, and polarization dependence. Issues affecting the performance of AWG device including crosstalk, insertion loss (IL), polarization dependent dispersion, polarization rotation, passband shape, and passband position.

#### 2.3.1 Crosstalk

The crosstalk of AWG may be caused by many mechanisms such as the truncation of mode field, mode conversion, phase distortion and the imperfections in the fabrication process (Zhou et al., 2007). However, the most obvious source of crosstalk is the coupling of the exponential tails of the field distributions between adjacent waveguides that depends on I/O waveguide separation and arrayed waveguide separation  $d$  along the interfaces of the slabs (see Figure 2).

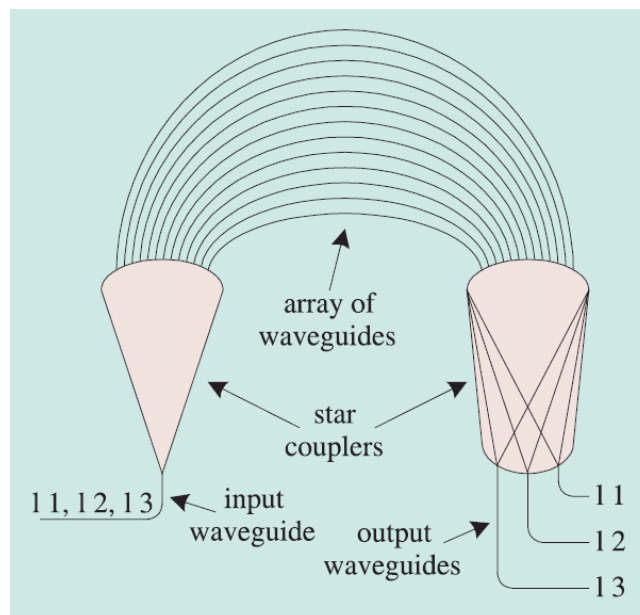


Fig. 2. Array waveguide illustration (Gorshe, 2006)

#### 2.3.2 Insertion loss (IL)

AWG can work as de(multiplexer) and router to combine and separate wavelength channels, play important roles as a key optical component. For such passive devices, lower insertion losses are desirable. The insertion loss also refers to the reduction in optical power between an input and output port of AWG in decibels (dB). The insertion losses of AWG are due to different factors such as the material intrinsic properties, bent waveguides, transition loss of star coupler and fiber-to-waveguide coupling loss. Many methods have been studied extensively to reduce the insertion loss, which include low-index contrast  $\text{SiO}_2$ -on-Si waveguide, high-index contrast waveguide with a spot-size converter, double-etched process, vertically etching the tapered waveguides, cascaded laterally tapered waveguide, and ultraviolet (UV)-tapered waveguide. These methods focus more specifically on the low-

loss coupling between fibers and AWG and the transition loss that occurs at the interface between the slabs and arrayed waveguides (Zhou et al., 2007).

### 2.3.3 Polarization Dependent Dispersion

Unless specifically engineered, waveguide boundary conditions cause quasi-TE and quasi-TM polarized modes to propagate at different speeds (birefringence), particularly in the case of strongly confining waveguides. As well as birefringence due to waveguide geometry, stresses within the structure may occur due to fabrication processes that can cause anisotropy and stress birefringence. Birefringence causes a second “shadow” spot on the output plane of the FPR, where the TE- and TM- like polarizations have experienced different phase shifts, potentially coupling with the wrong output waveguide and causing inter-channel crosstalk. Several methods have been presented to reduce this polarization dependence, such as making the Free Spectral Range equal the difference between the phase change between TE and TM polarized modes, hence overlapping the TE/TM spots, or using a polarization converting lambda half-plate half way along the AWs, causing both polarizations to undergo the same phase change. Stress birefringence in the waveguides is treated to some extent by coating the waveguides with a stress inducing film or, as covered in, in the case of silicon on Silica waveguides, stress-relieving grooves can be cut either side of the waveguide (Lidgate, 2004).

### 2.3.4 Polarization Rotation

Curved waveguides by their nature will exhibit a certain amount of Polarization Rotation, where the light energy is transferred from one polarization to the other. Polarization rotation in the curved waveguides of the AWG is an effect that has not presently been covered by any paper on the subject of AWGs even though it may be in some cases a contributor to dispersion in the device (Lidgate, 2004).

### 2.3.5 Passband Shape

A sharp passband, such as the one illustrated schematically in Figure 3a, allows very little error in laser frequency and AWG wavelength tolerance. It is desirable in most circumstances to flatten the passband, as illustrated in Figure 3b, so that the device produces a similar output for small changes in laser wavelength. The ideal shape for the passband of an AWG is to have a flat top, with a deviation of less than 1 dB, for over 70% of the channel separation, and as wide a -3 dB bandwidth (Full Width Half Maximum (FWHM)) as possible without increasing crosstalk (Lidgate, 2004).

### 2.3.6 Passband Position

Design or fabrication errors cause a phase error at the end of the AWs which may shift the focal point away from the expected position, hence affecting the passband position. To compensate for this, the position of the focal point may be shifted by adjusting the temperature of the AWG. If the phase error for each waveguide is random, causing the spot to defocus, then separate heaters for each individual Arrayed Waveguide may be implemented. However this approach increases the energy consumed by the device and requires additional control circuitry, increasing the cost of manufacture (Lidgate, 2004).

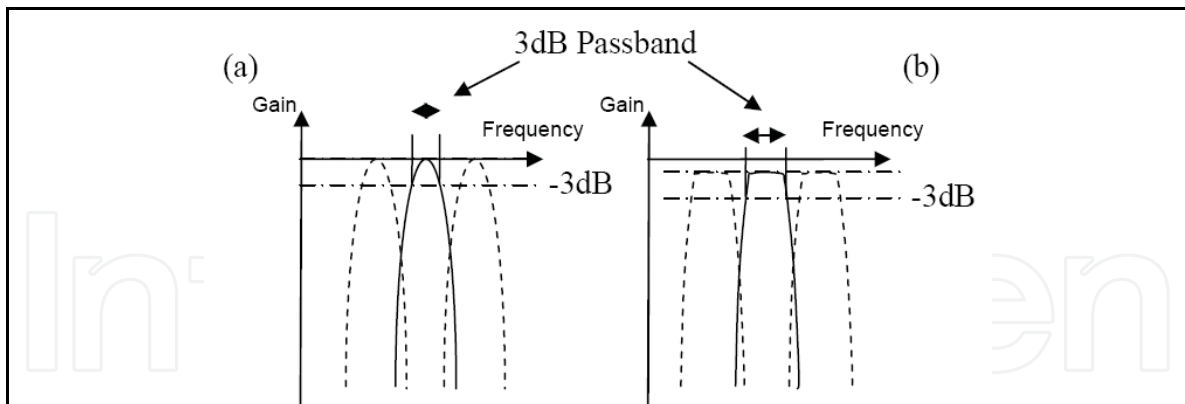


Fig. 3. AWG channel passband, (a) typical and (b) with flattened, widened, passband (Lidgate, 2004).

#### 2.4 AWG and Its Application in Optical Communication on Passive Optical Networks (PONs)

Since the Internet and broadband access network were introduced during the last decade, emerging applications, such as video on demand (VoD), digital cinema, telepresence, and high-quality audio transmission, demand high-throughput optical access networks with stringent quality of service (QoS) requirements. However, the infrastructure of current access networks suffers from limited bandwidth, high network management cost, low assembly flexibility, and bad network security, which obstructs the network from delivering integrated services to users (Zhang et al., 2006). Owing to the maturity of optical components and electronic circuits, optical fiber links have become practical for access networks.

PON is one of the most promising solutions for fiber-to-the-office (FTTO), fiber-to-the-home (FTTH), fiber-to-the-business (FTTB), and fiber-to-the-curb (FTTC), since it breaks through the economic barrier of traditional point-to-point (P2P) solutions (Zhang et al., 2006). FTTH technology using PON is the most promising way to provide high quality broadband access. PON has been early described for FTTH as early as 1986. The first trial PON system was developed and deployed by British Telecom around 1989. First generation PON systems were developed by both major equipment vendors and start-up companies. The first deployments of commercial PON systems targeted business customers. The market was relatively small, however, since it was uncommon to have a cluster of business customers wanting access to bandwidth greater than DS1/E1 that were all reachable by the same PON (Gorshe, 2006). Nowadays, PON is commonly deployed as it can offer a cost-efficient and scalable solution to provide huge-capacity optical access (Prat, 2007). The cost effectiveness of PON depends on numbers of optical network units (ONUs) per optical line terminal (OLT) optical transceiver, the cost of fiber and its installation, the cost of the DSL transceivers at ONU and subscriber premise equipments, the overall cost of powering ONU, and the real estate cost of placing the ONU (Gorshe, 2006).

PON has been standardized for FTTH solutions and is currently being deployed in the field by network service providers worldwide (Zhang et al., 2006). PON based on some multiplexing technologies, including wavelength division multiplexing (WDM), time division multiplexing (TDM), hybrid TDM/WDM, and optical code division multiplexing (OCDM). Even though time division multiple access (TDMA)-PON utilizes effectively the

bandwidth of fiber, it has limitations in its increased transmission speed, difficulty in burst synchronization, low security, dynamic bandwidth allocation (DBA) requirement and inaccurate Ranging (Assi et al., 2003 & Ohara et al., 2003).

#### 2.4.1 WDM-PON

Wavelength splitting (demultiplexing) and combining (multiplexing) are important functions in many optical applications. WDM enable optical de(multiplexing) in which the signals having different light wavelengths can be separated or combined to transmit in single optical fiber (Adam et al., 2008). WDM is an approach that can exploit the huge opto-electronic bandwidth mismatch by requiring that each end-user's equipment operate only at electronic rate, but multiple WDM channels from different end-users may be multiplexed on the same fiber (Mukherjee, 2000).

WDM technology was originally developed and emerged as a solution to the problem of fiber depletion, being able to channel multiple wavelengths over a single optical fiber pair. At the same time, this technology has proved to be able to offer high speed data transport over a single wavelength in the optical layer at rates four times of more than legacy networks such as synchronous digital hierarchy (SDH) or asynchronous transfer mode (ATM) (2.5 Gbps or 10 Gbps against typical 155 Mbps or 622 Mbps). Nonetheless, not all issues concerning this new technology have been adequately addressed, and despite its impressive potential, its interoperability with other networks, especially the IP network, is still an unsolved issue (Androulidakis & Kagklis, 2008).

WDM technology uses wavelengths to transmit data parallel-by-bit or serial-by-character, which increases the capacity of the fiber by assigning incoming optical signal to specific frequencies (wavelengths) within designated frequency band and then multiplexing the resulting signal out into one fiber. There are two alternatives for WDM metro networks: Dense WDM (DWDM) for high capacity and long haul transmission; while coarse WDM (CWDM) mean for shorter transmission and metro network (Lounsbury, 2003).

DWDM techniques are already adopted as the primary transmission medium in the backbone of commercial telecommunication networks. DWDM technology allows tens or hundreds of wavelength channels to be transmitted over a single optical fiber at a rate of 10 Gbps per channel and beyond. This means that the data rate can reach 10 Tbps in each individual fiber. Properly designed and administered can potentially take advantage of this enormous bandwidth made possible by the DWDM technology (Chen & Verma, 2008). However, DWDM is generally not suitable for the edge owing to the prevalence of "sub-wavelength" demands, for example, Ethernet-based service, storage area network (SAN) extension, and legacy private leased line (PLL) (Kasim, 2007).

CWDM allows the wavelengths to be spaced farther apart, which allows for economical solutions in sparse applications as compared to DWDM which utilizes very closely spaced wavelength (around 0.8 nm). Both CWDM and DWDM technology have their place in current and emerging metro-network infrastructure. When these technologies are used in combination with appropriate optical fibers, the economic benefits, which help to lower system costs, are significant (Lounsbury, 2003). AWG device is a key element for WDM systems in optical telecommunication.

The emerging WDM-PON becomes more favorable as the required bandwidth increases, but the technology comes at an extravagant price (Iwatsuki et al., 2004). In addition, the effect of statistical multiplexing is insignificant in multimedia communications



environments for WDM-PON. Even though WDM-PON has several advantages over TDM-PON, it has failed to attract attention from industries because of its high cost (Zhang et al., 2006).

#### 2.4.2 OCDMA-PON

OCDMA has been recently proposed as an alternative to frequency and time based multiple and multiplexing methods for next generation high speed optical fiber networks (Salehi, 1989; Salehi & Brackett, 1989). OCDMA system has attracted increasing attention in recent years due to the following advantages: asynchronous access capability, accurate time of arrival measurements, flexibility of user allocation, ability to support variable bit rate, busy traffic and security against unauthorized users. OCDMA is a very attractive multi-access technique that can be used for local area network (LAN) and the first one mile (Salehi, 1989). CDMA can provide multiple access to a network without using wavelength sensitive components as in WDM, and without employing very high speed electronic data processing devices as are needed in TDM network. CDMA achieves multiple accesses by assigning a unique code to each user. To communicate with another node, users imprint their agreed upon code onto the data. The receiver can then decode the bit stream by locking onto the same code sequence. The principle of OCDMA is based on spread spectrum techniques, it spreads the energy of the optical signal over a frequency band that is much wider than the minimum bandwidth required to send the information. This spreading is done by a code that is independent of the signal itself. Thus, an encoder is used to map each bit of information into a high rate (longer code length) optical sequence (Keiser, 2000).

The key advantage of using CDMA is that, CDMA can be encoded and decoded in optical domain without converting the signal to electronic unless it needs to be. This is extremely important because the electronic processing is much slower than the optical transmission rate. Due to this OCDMA has been recognized as one of the most important technologies for supporting many users in shared media simultaneously, and in some cases can increase the transmission capacity of an optical fiber (Salehi & Brackett, 1989).

OCDMA-PON allows each ONU to use a different signal rate and format corresponding to the subscriber's native client signal. OCDMA can also be used in conjunction with WDM for increased bandwidth capabilities. The concept behind CDMA is to carry multiple client signals with their transmission spectrum spread over the same channel. The symbols from the constituent signals are encoded in a manner that is recognizable by the decoder. The most amenable technique is direct sequence spread spectrum in which the symbols (e.g., 0 and 1) of each client signal are encoded as a longer string of symbols at a higher rate. Each ONU uses a different string value for its symbols. Fortunately, optical direct sequence OCDMA can be implemented with passive diffraction filters. A typical implementation uses Bragg diffraction grating, which can be constructed using UV exposure of standard single mode fibers through a mask with the desired pattern. Other grating types can also be used.

As illustrated in Figure 4, the encoder and decoder can use the same basic implementation. The signal is launched into one end of the filter. As the signal propagates through the filter, the grating pattern creates interference patterns as the light is reflected. The signal that reflects back out of the filter is thus modified in terms of both amplitude and phase, with the amount of symbol spread a function of the propagation time through the filter. At the receiver, the inverse operation converts the received spread spectrum symbol back into the original symbol (Gorshe, 2006).

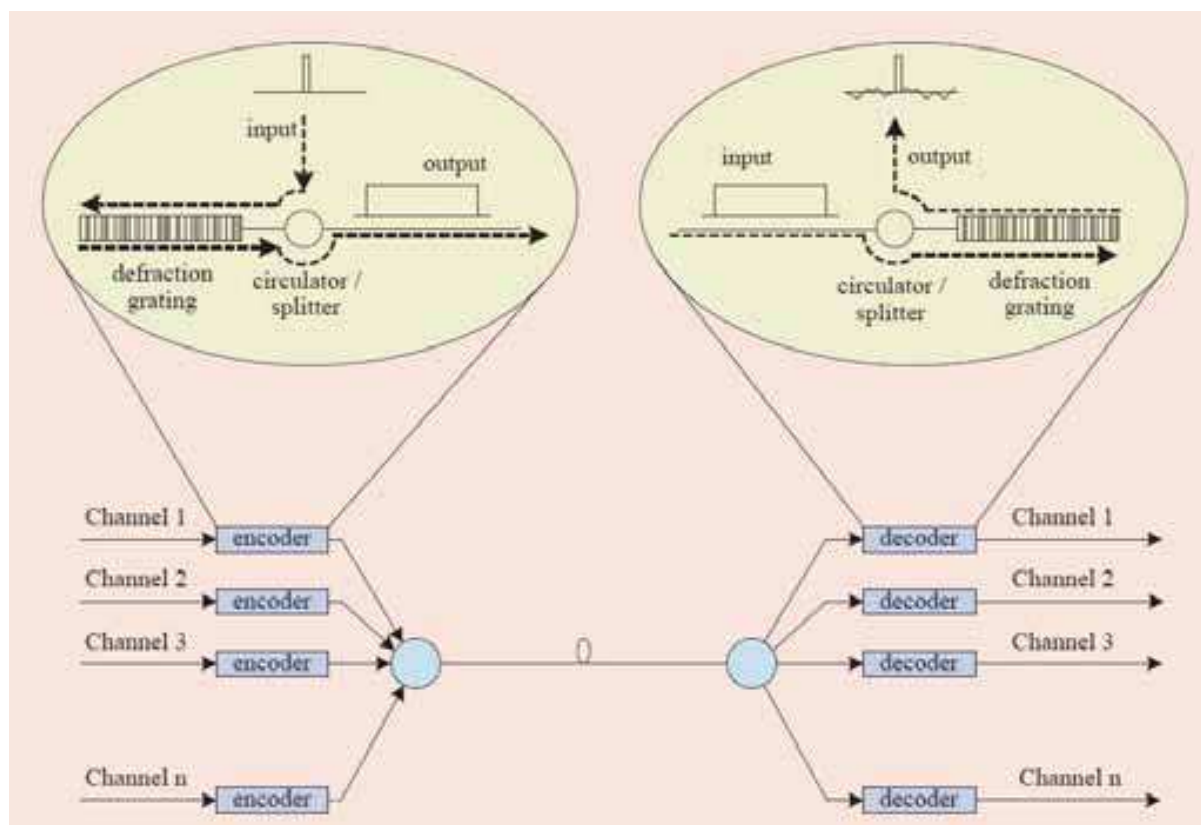


Fig. 4. OCDMA-PON illustration (Gorshe, 2006)

Due to the linearity of the Bragg filter, the spread spectrum bandwidth is proportional to the number of ONUs. The OLT splits the received optical signal to multiple diffraction filters in order to recover the data from the different ONUs. In a classical OCDMA implementation, the transmitter and receiver use identical Bragg gratings. More sophisticated receivers can use different gratings at the transmitter and receiver, and can use a combination of optical and electrical domain processing. Proper design of the grating patterns results in a system where the effects of crosstalk can be eliminated at the receiver. Temperature control of the grating is important, since physical expansion or contraction of the filter changes the effective pattern. This feature can also be exploited, however, to achieve tunable filters. (Other tuning mechanisms also exist.) The lasers in an OCDMA system, however, do not require frequency stability (Gorshe, 2006).

One major drawback to OCDMA-PON is that optical amplifiers are typically required to achieve an adequate signal to noise ratio. Due to the losses in the additional receiver splitter tree, circulators, and filters, ONUs per OLT splitter ratios without amplifiers are only in the 2:1 to 8:1 range. The receivers are also relatively complex. Consequently, they haven't proven to be as cost effective as some of the other alternatives (Gorshe, 2006).

### 3. AWGs-based OCDMA Encoding Device

#### 3.1 Design and Development of AWG-based OCDMA Encoding Device Prototype

A low-cost encoding device prototype is designed and developed for OCDMA systems using a 16-channels AWG device and optical switches. The optical switch only function with

a maximum receiving voltage source at 5 V. An adaptor device is used to convert the alternating current (AC) from the power supply to direct current (DC) and reduce the power supply from 240 V<sub>AC</sub> to 12 V<sub>DC</sub>. An IC 7805 voltage regulator circuit is designed to reduce the voltage output from adaptor device to 5 V for the optical switches as indicated in Figure 5. In this study, only one voltage regulator circuit is required for distributing the output voltage (5 V) to 16 different optical switches. This design not only required a small spacing, but also can reducing the electronic components.

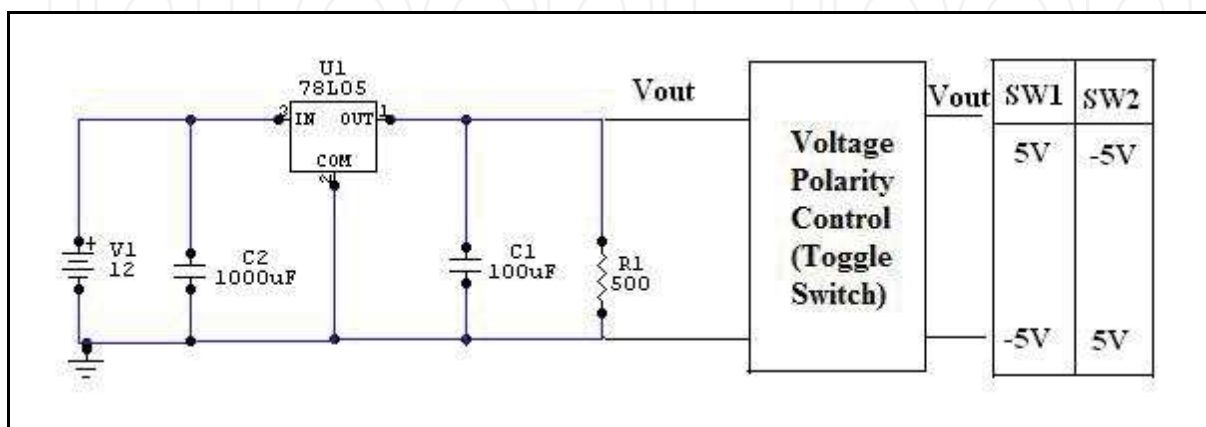


Fig. 5. Schematic diagram of voltage polarity control of IC 7805 voltage regulator circuit

The main purpose for voltage polarity control of voltage regulator circuit is to get an output voltage at +5 V or -5 V. The optical switch will automatically change (opposite) the polarization of voltage source from +5 V to -5 V. In the 16-channels encoder, each optical switch is control by a DPDT toggle switch. Therefore, 16 DPDT switches are required for 16 different optical switches. Output voltage (5 V) from voltage regulator circuit is distributed to 16 different DPDT switches evenly to activate 16 optical switches. The output voltage is 5 V when the switch 1 is push up, and alters to -5 V when the switch 2 is push down.

Each optical switch is connected to an input and two output representation links (Link 1 and 2). There are 8 pins of the optical switch responsible for controlling the polarization of voltage source. Among that, pin 1 and pin 8 are controlling the optical path exchange. When -5 V is provided to the optical switch, the input link is connected to link 1. On the other hand, the input link is connected to link 2 if +5 V is provided to the optical switch. The parameters of optical switch such energy switching, dissipation insertion, reflection losses, crosstalk, and switching time, play an important role in the optical switching.

### 3.2 Characteristics of AWG-based OCDMA Encoder Prototype

#### 3.2.1 Linearity Test for Two AWGs with Back-to-back (Serial) Connection

The linearity adjustment among two AWGs should proceed in designing an OCDMA encoder to assess counter their linearity's impact, although both AWGs' specifications are similar. The specifications used in the linear test for 16-channels AWG-based encoding device are listed in Table 1. The encoding device is consists of 1 input port and 16 output ports for AWG de(mux). Impact linearity testing is conducted to compare the shapes (wavelength forms) between the transmission signals and receiving signals according to the specifications as described in Table 2 before characterizing the encoding device.

First of all, the linearity test is conducted on a single AWG device to observe whether the AWG fulfill the key wavelength specifications as listed in Table 1 or not before connected with others. This test is important for identifying any failure or damaged in the device. The broadband laser source with center wavelength ( $\lambda_c$ ) 1550 nm is supply to 16-channels demux and then to a 16-channels mux before connected to OSA for analyzing the spectrum specifications (Figure 6). The multiplexer also can be represented by the combination of two 8x1 couplers and a 2x1 coupler as shown in Figure 7. Table 3 presented the  $\lambda_c$ , peak power, and different power for AWG back-to-back connection. The simulation result of AWG with channel spacing of 0.8 nm is shown in Figure 8. It showed the power output distribution of the 16-channels output waveguides, which indicate the simulated channel spacing of 0.8 nm. Thus, output wavelength for each channel followed ITU specification. Figure 9 to 12 depicted the spectrum displays and power plots on OSA.

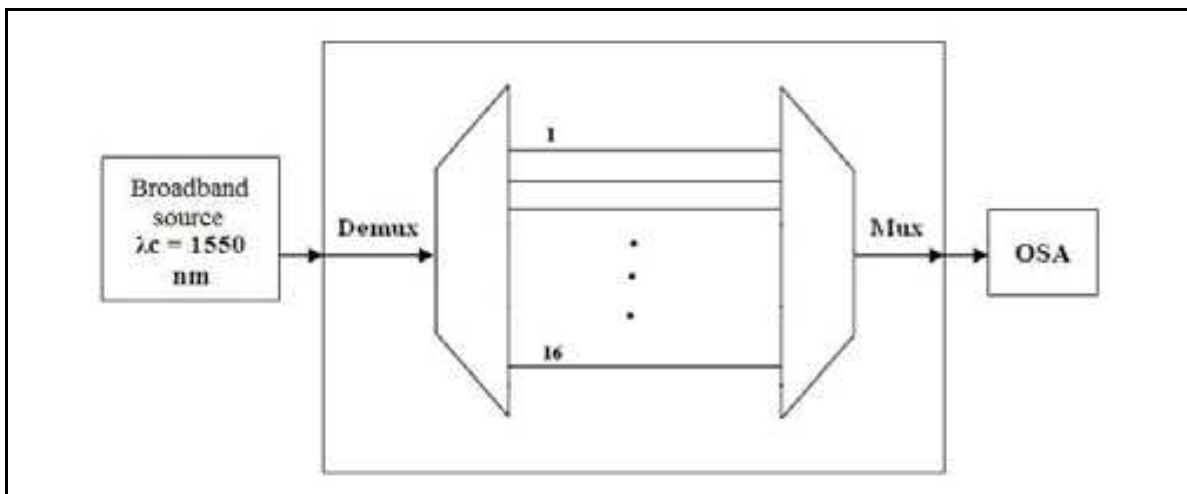


Fig. 6. The schematic layout of the linearity test for AWG with back-to-back connection

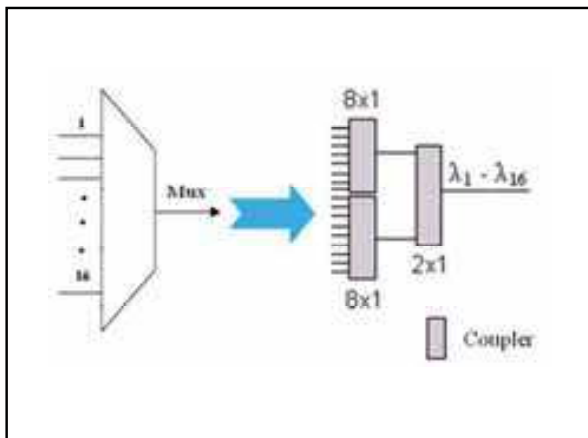


Fig. 7. The mux represented by combination three couplers

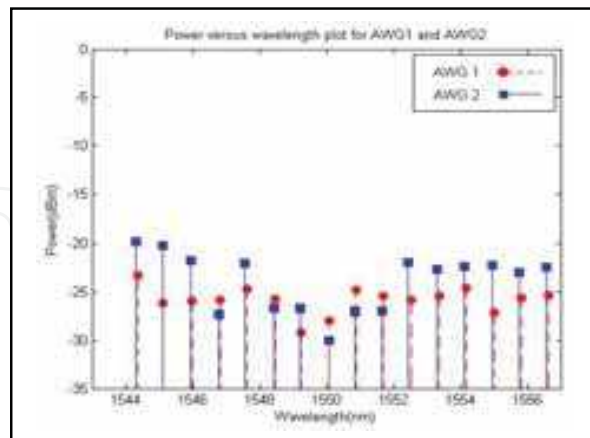


Fig. 8. Power vs. wavelength plot for AWG 1 and AWG 2

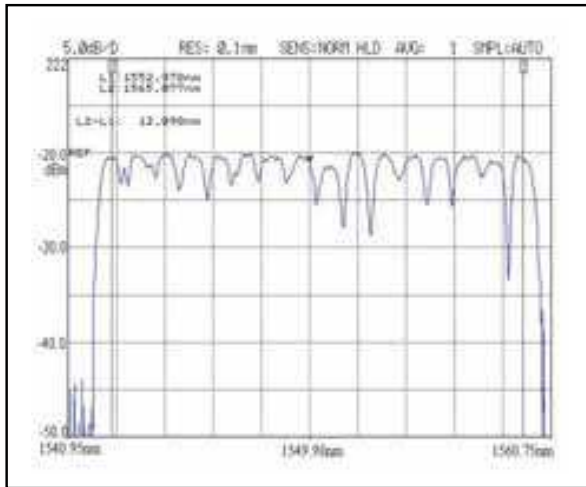


Fig. 9. The spectrum display for 16-channels AWG 1

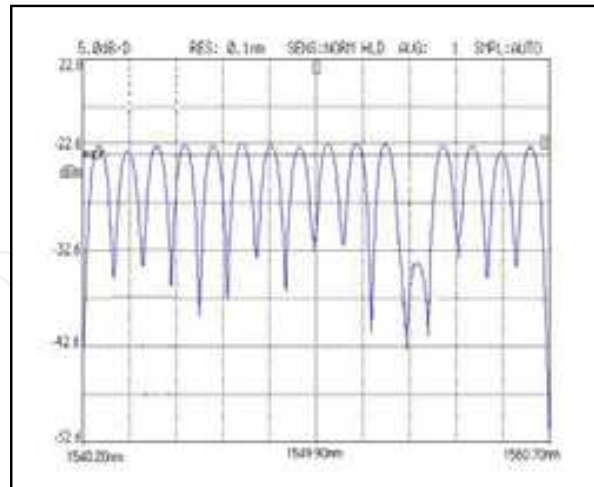


Fig. 10. The spectrum display for 16-channels AWG 2

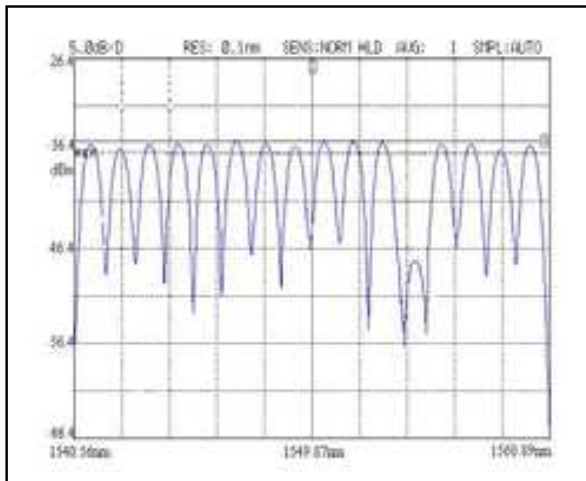


Fig. 11. The spectrum display for AWG back-to-back connection

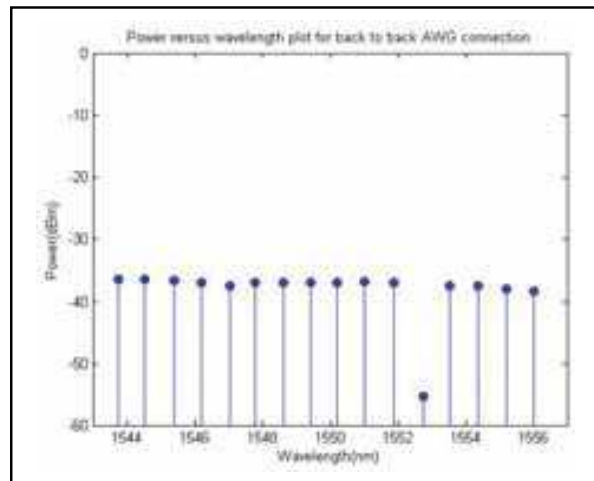


Fig. 12. Power vs. wavelength plot for AWG back-to-back connection

Wavelengths			
Channel	Spectrum (THz)	Measurement (THz)	$\Delta\lambda$ (GHz)
1	1548.515	1548.517	0.002
2	1549.315	1549.317	0.001
3	1550.116	1550.117	0.001
4	1550.918	1550.918	0.000
5	1551.721	1551.720	-0.001
6	1552.524	1552.523	-0.002
7	1553.329	1553.326	-0.003
8	1554.134	1554.130	-0.004
9	1554.940	1554.937	-0.003
10	1555.747	1555.742	-0.005
11	1556.555	1556.549	-0.005
12	1557.363	1557.358	-0.006
13	1558.173	1558.167	-0.006

14	1558.983	1558.977	-0.007
15	1559.794	1559.787	-0.007
16	1560.606	1560.599	-0.007

Table 1. Specification for 16-channels AWG

Channels	AWG 1		AWG 2		$\Delta\lambda_c$
	$\lambda_c$ (nm)	Peak Power (dBm)	$\lambda_c$ (nm)	Peak Power (dBm)	
1	1544.31	-19.81	1544.36	-23.3	0.058
2	1545.12	-20.22	1545.12	-26.11	0
3	1545.95	-21.78	1545.97	-25.9	0.024
4	1546.78	-27.36	1546.83	-25.86	0.049
5	1547.58	-22.01	1547.62	-24.7	0.042
6	1548.42	-26.69	1548.46	-25.77	0.033
7	1549.22	-26.8	1549.26	-29.26	0.031
8	1550.07	-30.05	1550.08	-27.97	0.009
9	1550.85	-27.06	1550.88	-24.82	0.033
10	1551.67	-26.92	1551.7	-25.45	0.03
11	1552.45	-21.91	1552.53	-25.86	0.077
12	1553.29	-22.63	1553.37	-35.44	0.078
13	1554.12	-22.33	1554.19	-24.57	0.073
14	1554.94	-22.25	1555.01	-27.12	0.073
15	1555.75	-22.97	1555.82	-25.68	0.077
16	1556.56	-22.49	1556.62	-25.32	0.068

Table 2. Center wavelength, peak power, and different power for AWG 1 and AWG 2

Channels	$\lambda_c$ (nm)	Peak Power (dBm)
1	1543.760	-36.40
2	1544.540	-36.40
3	1545.370	-36.70
4	1546.200	-36.90
5	1547.040	-37.40
6	1547.800	-36.90
7	1548.620	-36.89
8	1549.420	-36.87
9	1550.220	-36.87
10	1551.020	-36.80
11	1551.900	-36.90
12	1552.750	-55.40
13	1553.520	-37.50
14	1554.360	-37.50
15	1555.200	-37.94
16	1556.000	-38.40

Table 3. Center wavelength, peak power, and different power for AWG back-to-back connection

### 3.2.2 Continuous Signal Test

The parameters of the AWG-based OCDMA encoder such as insertion loss, OSNR, uniformity, and crosstalk are measured through a continuous signal test to increase the service reliability and efficiency of coding to make sure any information or data are correctly delivered. The instruments and measurement equipments such broadband source, TLS source, and OSA are used in the experiment as summarized in Figure 13 with the help of block diagram. The output signals from demux port are coded in binary form, either '1' or '0'. When +5 V is given, the optical switch will give '1' and '0' is given to -5 V. The coding is based on the voltage polarity control of voltage regulator circuit. All the output signals will be combined by mux and then analyzed in OSA to observe the spectrums' specifications.

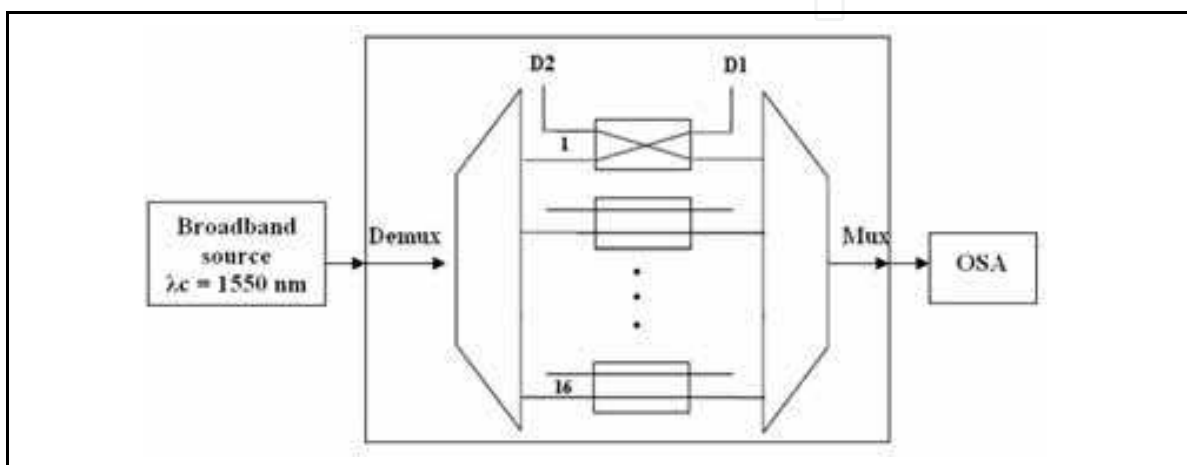


Fig. 13. Block diagram of continuous signal test for AWG-based OCDMA encoder

Each optical switch has 2 delay ports and each port is connected to an optical fiber line with specified range. The wavelengths from demux will be modulated with the binary code '1' in optical switches when voltage supply + 5 V are given. Then, the signals will move to the delay port (from port D1 to port D2) and returned to mux to deciphered and analyze in OSA. However, when voltage supply - 5 V are given, the signals still move to the delay port even though they don't modulate with the binary code. This paper only displays and discusses the spectrums for channel 9 to channel 16. Figure 14 illustrated the spectrums displays in OSA when broadband source is given with the binary code 11111111. The characterization will be carried out based on the coding. Each output signals from demux are given a different binary code and analyzed in OSA. The parameters of uniformity and crosstalk can be identifying through the spectrums display. Table 4 presented the  $\lambda_c$  and peak power for each passband of AWG-based OCDMA encoder.

Three parameters of the AWG-based OCDMA encoder: uniformity, crosstalk, and insertion loss, are measured in this test. Insertion loss uniformity, also known as non-uniformity, represents the difference between the maximum insertion loss,  $P_1$ , and minimum insertion loss,  $P_2$ , taken over all channels. The result indicates how evenly power is distributed at output. The uniformity measurement for AWG-based OCDMA encoder is shown in Figure 15, where:

$$\begin{aligned} \text{Uniformity} &= \text{Maximum peak power, } P_1 - \text{Minimum peak power, } P_2 \\ &= (-37.28) - (-38.91) = 1.63 \text{ dB} \end{aligned} \quad (1)$$

Crosstalk is measured the degree of isolation between the input at one port and the optical power scattered or reflected back into the other input port. The calculated crosstalk for AWG-based OCDMA encoder is less than 9.77 dB (see Figure 16).

Insertion loss (IL) denotes the loss in power each optical signal suffers as it moves through an AWG device. It is defined as the maximum loss within the channel passband for all polarization states and calculated as the difference (in dB) between the reference level (0 dB) and the measured output signal's point of lowest power within the passband. The value of wavelength for each port is acquired from the broadband source admitted into TLS source with input power 0 dB and the output power is listed in Table 5. The output power is the value for insertion loss. Theoretically, the insertion loss is measured for each device is used in testing. The loss for each optical switch is 1.2 dB and the patch cord cable absorbed 0.3 dB for each 3m. The connector loss is very small and can be neglected. The total losses:

$$\text{Total Loss} = [(1.2 \times 8) + (0.3 \times 2) + (5.0 \times 2)] \text{ dB} = 20.2 \text{ dB} \tag{2}$$

Channels	$\lambda_c$ (nm)		Passband		Peak Power (dBm)
	Spectrum	Measurement	3 dB	10 dB	
9	1544.94	1544.32	0.60	0.76	-37.69
10	1555.75	1555.13	0.56	0.76	-38.51
11	1556.56	1556.01	0.56	0.76	-38.91
12	1557.36	1556.79	0.60	0.76	-38.5
13	1558.17	1557.57	0.60	0.80	-37.28
14	1558.98	1558.41	0.56	0.80	-38.06
15	1559.79	1559.21	0.56	0.80	-37.77
16	1560.61	1559.99	0.56	0.80	-38.20

Table 4. Center wavelength and peak power of passband for 16-channels AWG-based OCDMA encoder

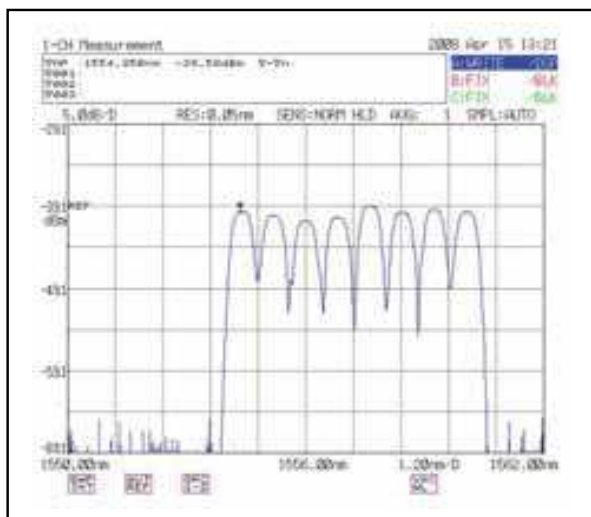


Fig. 14. Spectrum display for 8-channels AWG-based OCDMA encoder

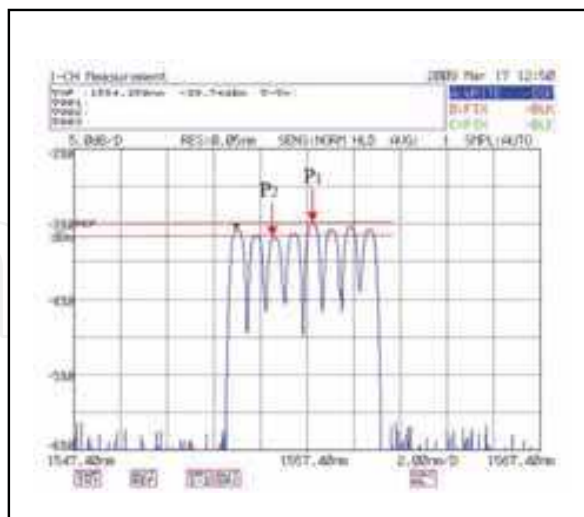


Fig. 15. The uniformity measurement for 8-channels AWG-based OCDMA encoder





Fig. 16. The crosstalk measurement for 8-channels AWG-based OCDMA encoder

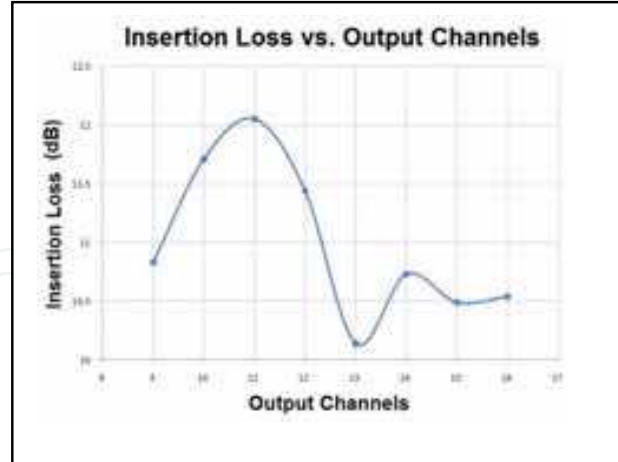


Fig. 17. Insertion loss vs. output channels plot

Channels	Wavelengths			Broadband Source		TLS Source		IL, dB
	Spectrum	Measurement	$\Delta\lambda$	$\lambda_c$ , nm	P, dB	$\lambda_c$ , nm	P, dB	
9	1554.940	1554.937	-0.003	1544.32	0.00	1554.33	-10.83	10.83
10	1555.747	1555.742	-0.005	1555.13	0.00	1555.14	-11.71	11.71
11	1556.555	1556.549	-0.005	1556.01	0.00	1556.02	-12.05	12.05
12	1557.363	1557.358	-0.006	1556.79	0.00	1556.80	-11.44	11.44
13	1558.173	1558.167	-0.006	1557.57	0.00	1557.59	-10.14	10.14
14	1558.983	1558.977	-0.007	1558.41	0.00	1558.42	-10.73	10.73
15	1559.794	1559.787	-0.007	1559.21	0.00	1559.23	-10.49	10.49
16	1560.606	1560.599	-0.007	1559.99	0.00	1560.01	-10.54	10.54

Table 5. Specification and insertion loss for 8-channels AWG-based encoder

The calculation for insertion loss is much more higher as compared to the experimental value. The insertion loss vs. output ports plot is indicated in Figure 17. The maximum insertion loss of 12.05 dB is at channel 11 and the minimum insertion loss of 10.14 dB is at channel 13.

### 3.3 Signals Selective and Spectral Encoding

256 binary codes can be produced from 8 optical switches, however according to the Enhancement Double-Weight (EDW) theory, only those codes consist 1 or 2 bit '1' can be used for data transmission, the others will repeat the same data in signal delivery. These codes will provide the voltage source to the optical switches either + 5 V or - 5 V. The characterizations for each code can be used in data transmission are listed in Table 6. Figure 17 to 22 showed the output spectrums that observed from OSA for data transmission based on EDW theory with wavelength between 1550 nm to 1562 nm.

Binary Code	OSNR (dB)
0000001	-20.00
0000010	-20.00
0000011	-20.00

0000100	-20.00
00001000	-20.00
00001100	-20.00
00010000	-19.07
00100000	-18.72
00110000	-20.00
01000000	-18.75

Table 6. Binary code for signal transmission and OSNR

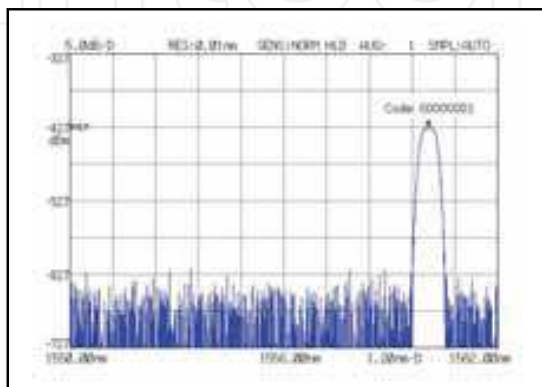


Fig. 18. Spectrum display for code 00000001

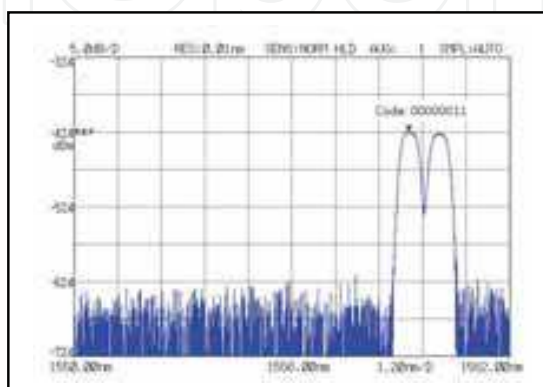


Fig. 19. Spectrum display for code 00000011

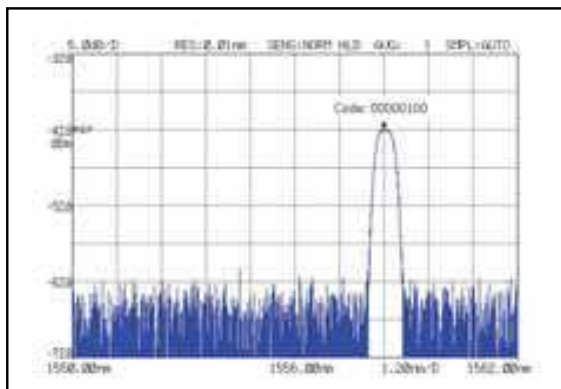


Fig. 20. Spectrum display for code 00000100

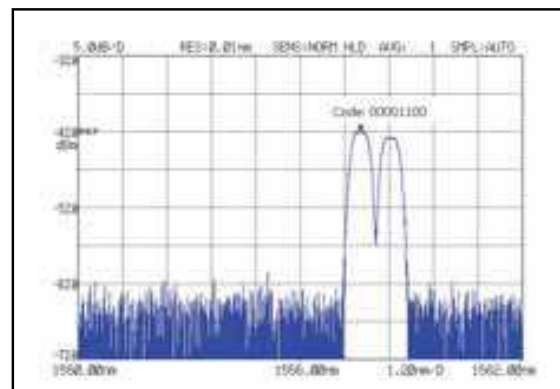


Fig. 21. Spectrum display for code 00000110

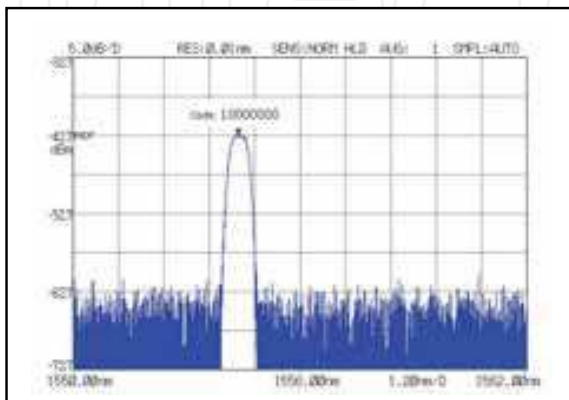


Fig. 22. Spectrum display for code 10000000

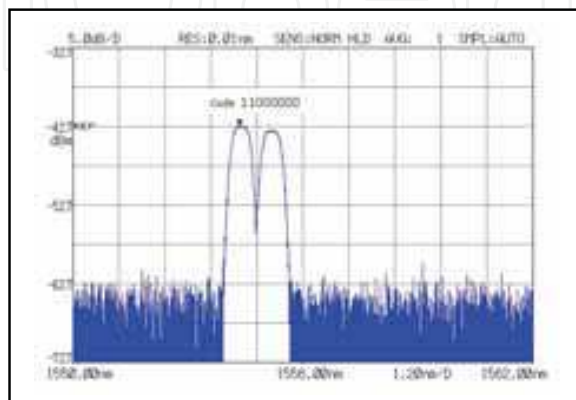


Fig. 23. Spectrum display for code 11000000

### 3.4 The Developed Prototype

A prototype was designed and developed to enable us to evaluate the performance in an actual propagation environment as illustrated in Figure 24 to 25. Using the developed prototype, we conducted a field experiment to investigate the technical feasibility. The parameters of the developed prototype in field experiment are shown in Table 7.

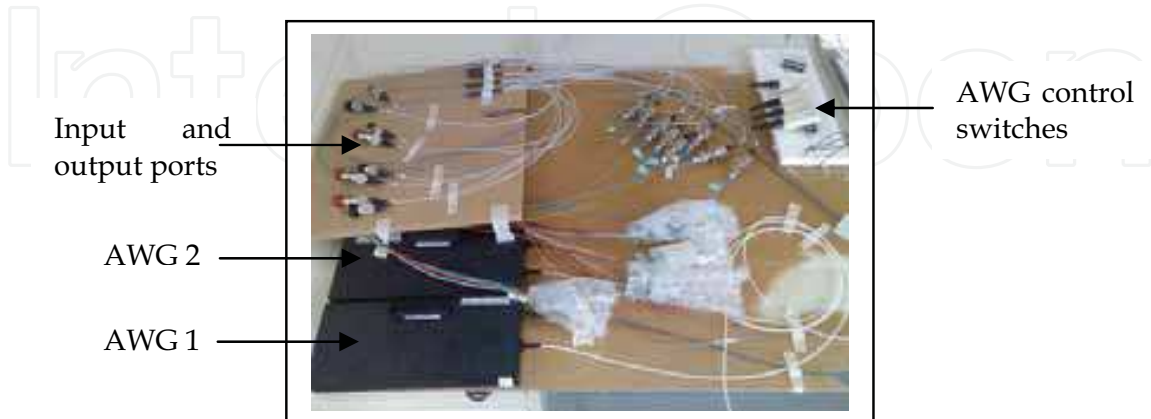


Fig. 24. Photographic view of AWG-based OCDMA encode prototype before chasing

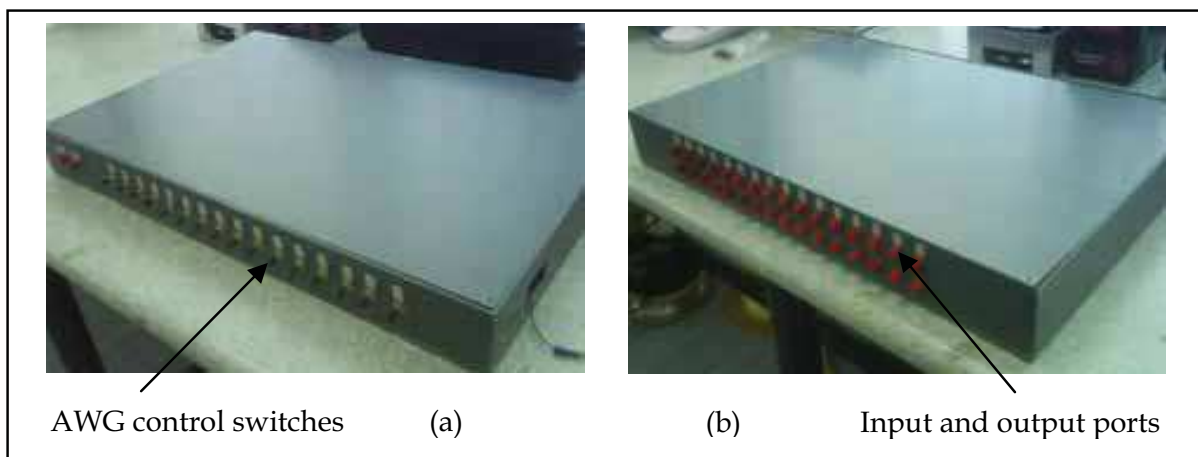


Fig. 25. Photographic view of AWG-based OCDMA encode prototype, (a) Front view and (b) back view

Type	OCDMA Encoder 8-Terminal
Wavelength Range	1540 nm -1560 nm
Insertion Loss	≤ 12.0 dB
Crosstalk	≤ 10.0 dB
OSNR	≤ 20.0 dB
Rated Voltage	± 5 V
Dimension	60 x 40 cm

Table 7. The parameters of the developed prototype

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