Wavelength-Interleaving Bidirectional Circulators

K. Tai, B. Chang, J. Chen, H. Mao, T. Ducellier, J. Xie, L. Mao, and J. Wheeldon

***Abstract*—We report a wavelength-interleaving bidirectional circulator, in which the even and odd ITU channels circulate in opposite handedness. Demonstrated three-port bidirectional isolation ranges from 45 dB for single-pass to 90 dB for dual-pass over the entire C-band with low loss, large flat-top bandwidth, low PDL, and good temperature stability. This new device technology is an enabler for bidirectional optical networks and opens up a range of possibilities for bidirectional fiber devices: isolators, circulators, add-drops, cross-connects, and uni- to bidirectional optical network interfaces.**

***Index Terms*—Optical fiber communication, optical fiber devices, optical filters.**

BIDIRECTIONAL transmission has many obvious advantages over the unidirection transmission [1]. However, bidirectional transmission on optical fiber has suffered from its sensitivity to backreflections. Backreflections, either localized (defective components or splices for example) or distributed (Rayleigh backscattering) could lead to cross talk between opposing transmitted channels (denoted as eastbound and westbound) and oscillation in bidirectional amplifiers [2]. A possible solution to alleviate the first problem would be to use a wavelength interleaving allocation scheme for eastbound and westbound transmissions. With this arrangement, the backreflection of eastbound channels would not affect the westbound propagating channels [1]. One of the obvious advantages of bidirectional wavelength interleaved $N/2$ dense wavelength division multiplexing (DWDM) over standard unidirectional N DWDM technology comes with the drastic reduction of nonlinear interaction between channels because the channel spacing is doubled in the bidirectional system [3]. Another obstacle for bidirectional transmission has been the lack of enabling optical fiber components such as the bidirectional amplifier. Erbium-doped fiber amplification (EDFA) process is inherently bidirectional as exemplified by the presence of both forward and backward propagating amplified spontaneous emission (ASE). However, the addition of isolators to prevent backreflection has made EDFA unidirectional. To achieve amplification for bidirectional transmission, different schemes have been proposed in the past [1]. One way is to build a ring using two circulators and two EDFAs as shown in Fig. 1(a) [2]. However, the constraint of oscillation still prevails. Therefore, bidirectional isolators [Fig. 1(b)] that would simultaneously block backreflected eastbound channels traveling west and backreflected westbound channels traveling east are needed to prevent oscillation in bidirectional amplifiers.

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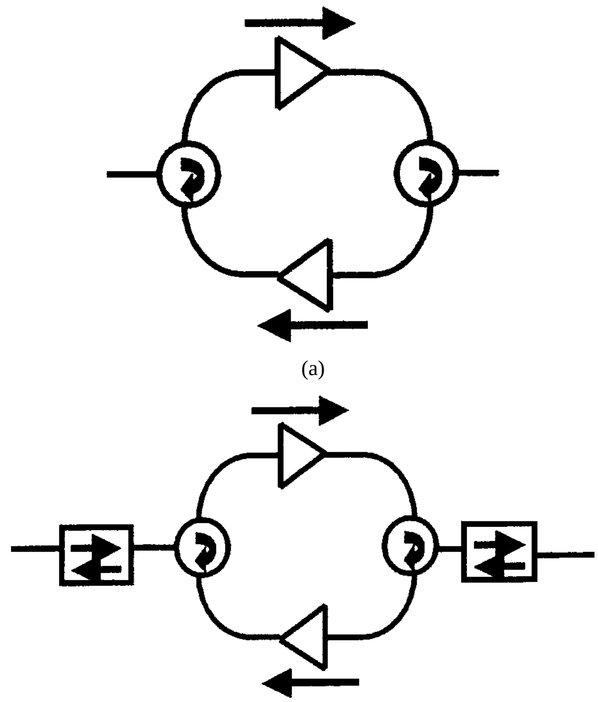

(a)

(b)

Fig. 1. (a) An existing scheme to realize amplification in wavelength interleaving bidirectional transmission using two circulators, (b) A new scheme with the additional bidirectional isolators.

In this paper we report a new class of passive nonreciprocal bidirectional circulators by combining the interleaver and circulator technologies. The wavelength-interleaving bicirculator technology is an enabler for bidirectional optical networks and opens up a range of possibilities for bidirectional fiber devices: isolators, circulators, add-drops, cross-connects, and uni- to bidirectional all-optical network interfaces [4].

The novel bicirculating function can be realized in device design shown in Fig. 2, which consists of a Lyot-Ohman birefringent optical filter, a nonreciprocal magnetic Faraday rotating garnet and polarization beam splitters. The Lyot-Ohman filter in this case is made of $(2n+1)$ crystals, $n \geq 1$, of length equal to $c/(\Delta n \mathrm{FSR})$, where c is the speed of light, Δn is the birefringence and FSR is the free spectral range [5]. In absence of the magnetic Faraday rotating garnet, the Lyot-Ohman filter and the polarization beam splitter provide the wavelength-interleaving filter function. With the magnetic Faraday rotating garnet, the device becomes a three-port bidirectional circulator. Note that between the ports 1 and 2 or between the ports 2 and 3, the device functions as a bidirectional isolator (bisolator). Based on this working principle and with the additional front-end polarization diversity, we have constructed three-port polarization-insensitive bicirculators with $\mathrm{FSR} = 200$ GHz. Westbound propagating even ITU channels would circulate from port 1 (west)

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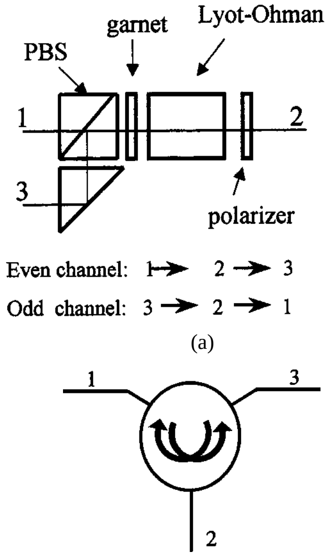

Fig. 2. (a) A three-port bicirculator optical layout. (b) The equivalent block diagram.

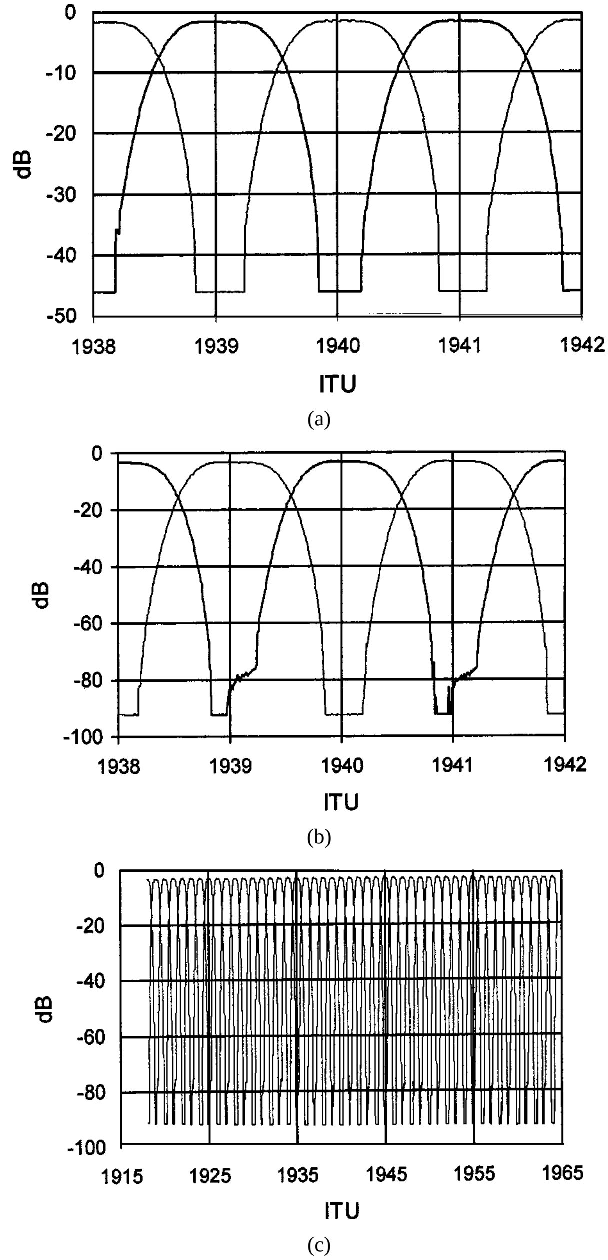

Fig. 3. (a) Single-pass transmission spectral characteristics of a three-port bicirculator west-to-common and common-to-west. (b) Double-pass west-to-common-to-east and east-to-common-to-west.(c) Same as (b) for full C-band.

to port 2 (common) to port 3 (east), whereas wavelength interleaved eastbound odd ITU channels would circulate from port 3 to port 2 to port 1. Figure 3(a) shows the two transmission spectra from the west to the common port and from the common to the west port. Non-reciprocal and wavelength-interleaving filter characteristic are clearly seen. Similar results were obtained for the east-to-common and for the common-to-east. An insertion loss of 1.6 dB per port connection was obtained with a peak isolation of about 45 dB. An accurate frequency alignment to the ITU grid was also seen. The material dispersion is small enough to allow the device to be ITU matched to be better than 5 GHz across the entire C-band. Furthermore, the design of this component is based on an athermal structure with typical temperature stability in the 5 GHz range from 0 to 70°C. Using the same circulator device, connecting a broadband mirror to the common port produces the equivalent of a dual-pass bidirectional isolator. Combining the experimental curves of the west-to-common and common-to-east and of the east-to-common and common-to-west, one can simulate the expected performance for dual-pass. The result is shown in Fig. 3(b) and (c). A 90 dB peak-to-valley isolation over the entire C-band is seen. By connecting two bicirculating devices, we have actually obtained instrument-limited 80 dB isolation measurement. The insertion loss for double pass is 3.1 dB, while the 60-dB isolation bandwidth would be in excess of 43 GHz. The polarization dependent loss, PDL, is less than 0.2 dB. It is interesting to note that this new bidirectional isolation technology provides a significantly more uniform isolation performance over a larger wavelength range (at least more than the entire C-band demonstrated) than conventional unidirectional isolation technology.

As stated in the introduction, the major obstacles to the wide deployment of bidirectional networks have been the extreme requirement on backreflections throughout the network and the lack of passive optical components. With the proposed technology, these are completely alleviated. For example, a bad backreflection component can now be isolated from the optical amplifiers by sandwiching it between two bisolators shown in Fig. 1(b). The flexibility in isolation level (single or dual pass) and location will greatly facilitate network design and reduce overall cost.

The bicirculator can also be used in a large range of new applications. Basically a standard (i.e., designed for unidirectional networks) reflective device can be connected to the common port of bidirectional circulator to become a bidirectional component. This will again greatly reduce the overall cost of bidirectional networks since the same optical devices can be used both for uni- or bidirectional DWDM systems. Typical examples of such applications would be devices including fiber Bragg gratings or thin film filters. This would enable the realization

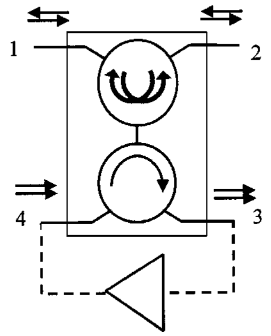

Fig. 4. A four-port device made of a bicirculator and an ordinary circulator. Connecting the port 3 and port 4 with an EDFA, this device becomes a bidirectional EDFA.

of bidirectional add-drop nodes where any wavelength can be added or dropped at a node, regardless of its propagation direction. Other applications of the bicirculator could be found for network monitoring, dynamic gain equalization, dispersion compensation, etc.

Another important application of the bicirculator is to provide a transparent all-optical interface to interconnect bi- and unidirectional optical networks. The layout of this four-port device is shown in Fig. 4. It requires both a bicirculator and an ordinary circulator. The operation of the device is as follows. For westbound propagating channels, the light travels from port 1 to port 3 and port 4 to port 2, whereas for the wavelength interleaved eastbound propagating channels, the light travels from port 2 to port 3 and port 4 to port 1. Ports 1 and 2 are connected to bidirectional traffic, whereas ports 3 and 4 are unidirectional. This four-port device transforms any unidirectional transmission device into a bidirectional one by feeding the light from port 3 through the optical device and then connecting it to port 4. For example, one can achieve bidirectional amplification using standard (single-directional) EDFA. This has been experimentally confirmed and will be reported in future publication. This would definitely provide large savings for the implementation of bidirectional networks, since current commercially available DWDM components could be reused for bidirectional networks. In addition, the four-port device realizes a network interface between wavelength interleaved bidirectional networks and standard DWDM networks. It could now be envisaged to have a bidirectional backbone connected to local DWDM unidirectional networks with a transparent all-optical interface.

In summary, we have shown a new enabling component technology for wavelength-interleaving bidirectional networks. Some potential applications have been described and are believed to ease considerably the constraints for bidirectional system design while enabling a new range of functionalities.

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