Integrated MQW Optical Amplifier/Noise-Filter/Photodetector Photonic Circuit

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***Abstract*—A monolithically integrated photonic circuit with an InGaAs / InGaAsP multiple-quantum-well (MQW) traveling-wave optical amplifier, a Bragg reflection grating-folded noise filter, and an MQW photodetector has been demonstrated. This photonic circuit offers potential as a preamplfiied lightwave receiver.**

OPTICAL receivers are key components for lightwave systems and future optical networks. Erbium-doped fiber preamplifiers provide excellent performance, yet their cost may be an issue in single-channel (wavelength) systems. With improvement in polarization performance and fiber-coupling loss, semiconductor optical amplifiers may offer an attractive alternative solution, especially if a completely integrated (single-chip) optical receiver subsystem, including optical amplifier, noise filter, and photodetector, could be economically realized. Such circuits may also be useful for wavelength-division-multiplexed (WDM) applications where the noise filter functions additionally as a wavelength channel selector. Toward that end, we report the first demonstration of a photonic circuit that integrates an InGaAs/InGaAsP multiple-quantum-well (MQW) traveling-wave optical amplifier, a Bragg reflection grating-folded directional-coupler noise filter, and an MQW photodetector.

A key issue of amplifier-based photonic integrated circuits is avoiding on-chip reflections back into the amplifier. This is particularly crucial when integrating noise filters, which are necessary for filtering the amplified spontaneous emission (ASE) noise adversely generated by the amplifier. In-line distributed Bragg reflection (DBR) gratings provide a simple and effective channel waveguide filter mechanism. However, a simple in-line grating filter is not appropriate, because it provides the complement of the desired transmissive passband filter response. The grating-folded directional-coupler filter [1] that combines two identical Bragg reflection gratings on the output arms of a 3-dB coupler can provide the desired narrowband filter response without unwanted reflection back to the amplifier. This filter is also potentially tunable with current injection into the gratings and is relatively compact, because it employs optical channel waveguides. An alternative approach to avoid reflection back into the amplifier is to use an aspheric integrated lens followed by an off-axis Bragg reflection grating [2] or a blazed and curved grating [3], [4] to focus and redirect light to a photodetector. Although necessary for multiwavelength receivers, these approaches use planar slab waveguides, which may require a larger chip area. It is worth noting that another candidate for the noise filter is the vertical-coupler filter (VCF) [5], which is not based upon reflections. The VCF, however, requires greater filter length to achieve the same filter bandwidth as that of the DBR filter.

The demonstrated photonic circuit is shown schematically in Fig. 1. Light incident into the input waveguide is amplified in the traveling-wave MQW amplifier section. The amplified light with ASE noise propagates to the 3-dB coupler and splits into each Bragg reflection grating filter section. The effect of the grating-folded filter is to reflect light over a narrow bandwidth determined by the grating stopband into the output waveguide and photodetector, suppressing the ASE noise. Just as importantly, no light is reflected back to the amplifier at any wavelength, provided that the optical path length from the coupler to the grating is equal for both arms and that the coupler splits light exactly at a 50:50 ratio. The photodetectors integrated downstream from the gratings on each arm of the coupler are for diagnostic purposes only. Note that in the present implementation, the output MQW photodetector can be viewed either as a photodetector or as an amplifier, depending upon the electrical drive. Therefore, this circuit can also function as a tandem optical amplifier with intermediate noise filter for high-gain, high-power amplification.

The circuit is fabricated from an atmospheric pressure MOVPE-grown wafer using the integration technology of

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[6]. The passive backbone optical waveguide is a 3-μm wide buried-rib structure, 0.3-μm thick 1.3-Q InGaAsP layer (λ_{PL} = 1.3-μm photoluminescence wavelength) with a 300-Å rib-loading layer formed on an n-InP substrate. The amplifier and photodetector sections consist of six compressively strained InGaAs/InGaAsP quantum-wells grown on top of the backbone waveguide, formed in a buried heterostructure. The input amplifier (or the output photodetector) and the diagnostic rear photodetectors are 420 μm long and 135 μm long, respectively. Buried-heterostructure waveguides under the input amplifier and the output photodetector are laterally separated by 150 μm for a future optical fiber coupling using a V-grooved structure. The 3-dB splitter is a 435-μm long zero-gap coupler [7] with input and output waveguide bends of lengths 1180 μm (radius of curvature $R = 4.7$ mm) and 350 μm ($R = 4.1$ mm), respectively. The 2300-Å pitch Bragg grating (Λ, Fig. 1) is written holographically on the rib-loading layer, and then is defined by wet chemical etching. The lateral separation between the two waveguide arms under the grating is 15 μm. After two MOVPE regrowths for current blocking using semi-insulating (SI) InP and for cladding and p-contact layers, gold contacts are deposited and patterned. Finally, the chip is proton-implanted for electrical isolation among the active sections. The input–output facet is antireflection (AR) coated with a single SiO layer. The total chip length is 4 mm.

Light from a tunable color-center laser was injected into the input waveguide arm with a 150-mA current applied to the amplifier section. The light was properly adjusted to be TE-polarized because the TE gain dominates in the compressively strained MQW gain material. The light-induced photocurrent was measured at the photodetectors by using a lock-in amplifier. The split-ratio of the coupler was determined to be 45 : 55 by the relative photocurrent measured at the through-and cross-diagnostic photodetectors, assuming the same sensitivity for each photodetector. Although the coupler was designed to be adjustable by current injection, the split-ratio of the chip studied here improved little with applied current to the coupler. The amplified and noise-filtered response of the photonic circuit measured by the integrated output MQW photodetector as a function of scanned input wavelength is shown in Fig. 2. The passband was centered at 1.527 μm with a filter bandwidth (FWHM) of 15 Å. The sidelobes were below −11 dB and the rejection ratio (the ratio of the output intensities at the peak and out of the passband wavelength) was 19 dB. The intensity reflectivity (R_G) of the Bragg reflection gratings was measured to be 0.7 from the transmission at the diagnostic photodetectors. By comparing the photocurrent for the same incident light into the input waveguide at the input amplifier used as a photodetector and at the integrated output photodetector with a 150-mA amplifier current to the input amplifier, the on-chip net loss was estimated to be 11.3 dB in the present device.

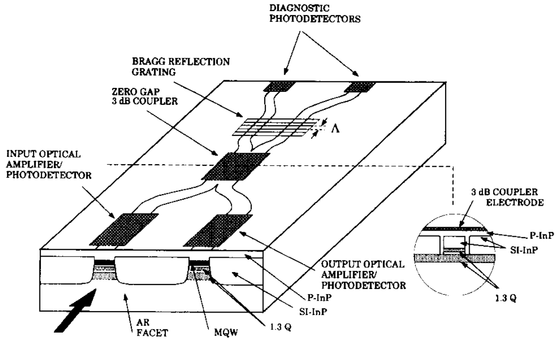

Fig. 1. Schematic diagram of the monolithically integrated photonic circuit with MQW optical amplifier, Bragg reflection grating-folded directional-coupler noise filter, and MQW photodetector.

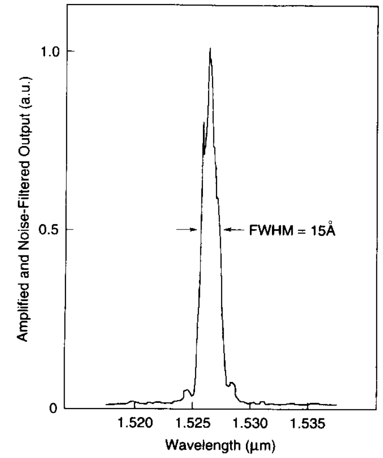

Fig. 2. Amplified and noise-filtered response of the photonic circuit measured by the integrated output MQW photodetector.

While the present circuit has demonstrated the feasibility of integrating the key elements of a preamplified lightwave receiver, clearly the loss of the integrated circuit must be reduced. The estimated maximum gain of the amplifier was ~ 13 dB for the applied amplifier current of 150 mA. The loss (or the output signal degradation) due to the 45 : 55 coupler split-ratio and the Bragg reflectivity of $R_G = 0.7$ was theoretically evaluated as 0.04 dB (negligibly small) and 1.55 dB, respectively. The bulk of the additional loss was attributed to propagation loss and fabrication imperfections, including waveguide bending loss and insertion loss in the directional coupler and Bragg reflection gratings. In addition, imperfect alignment of the Bragg grating can contribute to loss. Perpendicular alignment of the grating to the waveguides is required to keep the optical path length from the coupler to the grating equal for both arms. Unequal path length results in light reflected from the gratings being coupled back into the input waveguide [1], causing signal degradation at the output photodetector as well. Using contact-print grating technology [8] with alignment marks on a mask, such misalignment problem can be alleviated. In order to improve the overall fiber-to-chip gain (loss), the fiber coupling loss should also be considered. Using a micromachined, aspheric-lensed fiber [9], nearly > 90% (−0.45 dB) coupling efficiency can be obtained.

We have demonstrated a monolithically integrated photonic circuit with an InGaAs/InGaAsP MQW traveling-wave optical amplifier, a Bragg reflection grating-folded directional-coupler noise filter, and an MQW photodetector for a potential preamplified lightwave receiver. This photonic integrated device may be attractive in high data-rate optical networks and lightwave systems because of its compactness and potentially low cost.

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Controlled Nonlinearity Monolithic Integrated Optoelectronic Mixing Receiver

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Abstract—**A novel monolithic integrated optoelectronic mixing receiver with low conversion loss is demonstrated. It consists of a GaAs MSM photodetector mixer and a two-stage transimpedance preamplifier. By modulating the bias of the MSM photodetector with a local oscillator, the information signal on an optical carrier is down-converted to an electrical intermediate frequency. The mixing receiver nonlinearity can be controlled by simply changing the bias values to the MSM photodetector. The optoelectronic mixer has applications in subcarrier multiplexed lightwave distribution systems.**

IN A SUBCARRIER multiplexed (SCM) lightwave distribution system, the entire signal set on the optical carrier is detected and amplified by using a wideband optical receiver. An electronic mixer is used to down-convert the signal outputs from the receiver to an intermediate frequency (IF). A major advantage of SCM systems compared with high-speed baseband digital transmission is that existing RF and microwave electronics can be applied, and therefore high design flexibility and low cost are expected [1]–[3].

The requirement for a wideband optical receiver is an impediment to low cost. The optical receiver can be simplified by using an optoelectronic mixer (OEMixer), which performs the detection and frequency conversion simultaneously. With the OEMixer, the information signal carried by the optical carrier is converted directly to the electronic IF in the process of detection. The wideband receiver amplifier can be replaced by a cost-effective narrow-bandwidth IF amplifier. As a result, the noise performance of the system can be improved. OEMixers have been reported using optical amplifiers [4], avalanche photodiodes [5], GaAs photoconductors [6], [7] and GaAs metal semiconductor metal photodetectors (MSM PD's) [8].

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