InP-based monolithically integrated tunable wavelength filters in the 1.6–1.8 μm wavelength region for tunable laser purposes

Citation for published version (APA):

Tilma, B. W., Jiao, Y., Veldhoven, van, P. J., Smalbrugge, B., Ambrosius, H. P. M. M., Thijs, P. J. A., Leijtens, X. J. M., Nötzel, R., Smit, M. K., & Bente, E. A. J. M. (2011). InP-based monolithically integrated tunable wavelength filters in the 1.6–1.8 μm wavelength region for tunable laser purposes. *Journal of Lightwave Technology*, 29(18), 2818–2830. <https://doi.org/10.1109/JLT.2011.2162819>

DOI:

[10.1109/JLT.2011.2162819](https://doi.org/10.1109/JLT.2011.2162819)

Document status and date:

Published: 01/01/2011

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

InP-Based Monolithically Integrated Tunable Wavelength Filters in the 1.6–1.8 μm Wavelength Region for Tunable Laser Purposes

Bauke W. Tilma, *Student Member, IEEE*, Yuqing Jiao, *Student Member, IEEE*, Peter J. van Veldhoven, Barry Smalbrugge, Huub P. M. M. Ambrosius, Peter J. Thijs, Xaveer J. M. Leijtens, *Member, IEEE*, Richard Nötzel, Meint K. Smit, *Fellow, IEEE*, and Erwin A. J. M. Bente, *Member, IEEE*

Abstract—In this paper, we present the design, fabrication, and characterization of two monolithically InP-based integrated electro-optically tunable filters. The combination of these filters can be used to achieve a filter with a narrow passband and a large free spectral range. These filters are designed to be used in an integrated tunable laser source in the 1600–1800 nm wavelength region using active-passive integration technology. The fact that these filters worked successfully shows that this integration technology, originally designed to be used around 1550 nm wavelength, can also be used successfully in the 1600–1800 nm wavelength region without a large penalty in performance. The two filters, a high-resolution arrayed waveguide grating-type filters and a low-resolution multimode interferometer-tree-type filter are made tunable using 5 mm long electro-optic phase modulators in the arms of the waveguide arrays. Measurements show that these filters can be tuned over a wavelength range of more than 100 nm with an accuracy of 0.1 nm (1% of the free spectral range) for the high-resolution filter and an accuracy of 9 nm (4% of the free spectral range) for the low-resolution filter.

Index Terms—Electro-optic filters, integrated optoelectronics, laser tuning, optical filters.

I. INTRODUCTION

MONOLITHICALLY integrated tunable optical filters are an active research area already for over 20 years. Two important applications where a fast (down to nanoseconds) tunable integrated filter is desirable are the monolithically integrated

continuous tunable lasers [1] and more recently also all-optical wavelength routing in wavelength-division multiplexing systems [2]. The demand of lasers that can be tuned continuously and rapidly is currently growing quickly due to the increase in the use of such coherent light sources in measurement systems. Examples are the use of scanning laser sources in medical imaging such as frequency-domain optical coherence tomography (FD-OCT) for ophthalmology [3] and spectral imaging in dermatology and hematology [4]. Also, in other measurement systems such as gas sensing [5] and fiber Bragg strain sensing [6], fast scanning tunable lasers are required. In order to realize a monolithically integrated continuously tunable laser, a semiconductor-based wavelength filter has to be integrated. Currently, there are three types of monolithically integrated wavelength selective components that have been demonstrated and applied: the tunable distributed Bragg reflector (DBR) [1], the tunable ring resonator [7], and the more complex tunable arrayed waveguide grating (AWG) [8]. For hybrid integrated tunable laser sources, it has to be noted that the microelectromechanical systems in hybrid integrated tunable laser sources can be a good alternative as, e.g., discussed in [9].

Tunable DBRs and more complex related structures such as the sampled grating DBR (SG-DBR) are most often used as intracavity tuning elements in a laser cavity. Such DBRs are tuned by current injection where the injected carriers cause a change in the refractive index of the grating elements. Typically, two different DBRs have to be combined to realize a widely tunable laser using the Vernier principle [1]. Another option is the digital supermode DBR laser that uses a tunable DBR in combined with a relatively broadband digitally chirped grating to realize a widely tunable laser [10]. For OCT, a continuous tuning over many tens of nanometers is required. This is however more difficult to achieve with the Vernier-like effect that is used in Bragg grating-based devices.

A second drawback of the tuning technique though current injection in the DBR mirrors is that heat is generated in the waveguide thus changing its temperature. Also, the injected carriers have an effect on the total roundtrip gain in the laser [11]. The amount of heat depends on the amount of current and, therefore, on the detuning of the DBR. Since the relaxation of the temperature to equilibrium typically takes milliseconds in these devices, tunable lasers with DBR type of filters can have a stabilization time in the order of milliseconds. Furthermore, due to ageing the current-detuning relation of the DBRs changes over time, and this has to be corrected for over the lifetime of the device.

Manuscript received March 23, 2011; revised June 30, 2011; accepted July 16, 2011. Date of publication July 25, 2011; date of current version September 07, 2011. This work was supported by the IOP Photonic Devices program managed by the Technology Foundation STW and NL Agency, Dutch Ministry of Economic Affairs.

B. W. Tilma was with the COBRA Research Institute, Eindhoven University of Technology, Eindhoven 5600 MB, The Netherlands. He is now with the Eidgenössische Technische Hochschule Zürich, CH-8093 Zürich, Switzerland (e-mail: b.tilma@phys.ethz.ch).

Y. Jiao is with the COBRA Research Institute, Eindhoven University of Technology, Eindhoven 5600 MB, The Netherlands, and also with the Centre for Optical and Electromagnetic Research, Zhejiang University, Hangzhou 310058, China (e-mail: yqjiao@zju.edu.cn).

P. J. van Veldhoven, B. Smalbrugge, H. P. M. M. Ambrosius, X. J. M. Leijtens, R. Nötzel, M. K. Smit, and E. A. J. M. Bente are with the COBRA Research Institute, Eindhoven University of Technology, Eindhoven 5600 MB, The Netherlands (e-mail: p.j.veldhoven@tue.nl; e.smalbrugge@tue.nl; h.p.m.m.ambrosius@tue.nl; x.j.m.leijtens@tue.nl; r.noetzel@tue.nl; m.k.smit@tue.nl; e.a.j.m.bente@tue.nl).

P. J. Thijs is with the Photonics Labs, Philips Innovation Services, High Tech Campus, Eindhoven 5656 AE, The Netherlands (e-mail: peter.j.thijs@philips.com).

Digital Object Identifier 10.1109/JLT.2011.2162819

AWG filters can also be used in tunable lasers. When an active/passive integration scheme is used in the fabrication such a passive optical filter can be combined on a single chip with an optical amplifier [12], [13]. AWGs can be tuned in different ways. The simplest way is to change the temperature of the AWG [14]; however, the tuning speed is limited by the change of temperature in time, which is in the millisecond range. The tuning range of an InP-based AWG is limited by the operating temperature range and the approximate $0.12 \text{ nm}/^\circ\text{C}$ detuning of the AWG wavelength [15]. A better approach for the use in a tunable laser is the introduction of a series of phase modulators (PHMs) in each arm of the AWG [8]. As will be discussed, by introducing a linear increasing phase shift over the series of PHMs, the AWG can be continuously tuned over its total free spectral range (FSR) to a desired wavelength. The PHMs in these AWGs can be current or voltage controlled. In case of current control, the phase shifting is based on carrier injection which introduces carrier-induced effects [2]; however, this brings the same issues as with tunable DBRs. In the case of a voltage-controlled PHM, the phase shifting is based on field-induced effects [16]. The advantage of reverse-biased-controlled PHMs is the relatively low current (in the nanoampere to microampere range for reverse bias and in the 1–10 mA range for forward bias) which flows through a PHM. This makes that there is negligible heat dissipation which prevents unwanted temperature tuning of the filter, which reduces the settling time of the filter and improves its long-term stability. Furthermore, the switching speed of the PHMs in reverse bias can be up to several tens of gigahertz and theoretically up to 200 GHz [17], [18], whereas in forward bias the switching speed is limited to 1 GHz [2].

An AWG has a periodic transmission spectrum. Consequently, for wide tuning ranges such as those required for FD-OCT, a combination of two filters will have to be used to select one of the transmission peaks of the AWG. With the combination of two filters, very large continuous tuning ranges of over 200 nm can be realized. Obviously, there are also disadvantages of such tunable AWG filters. They tend to be relatively large, due to the length of voltage-controlled PHMs which can be up to several millimeters and the large number of waveguides required. Also, a fairly large number of electrode voltages needs to be accurately controlled.

Another important aspect is the wavelength scan range required in applications such as OCT. OCT imaging is typically applied in material that has a high water content and that is highly scattering. This makes that the wavelength range around 1700 nm is of interest for OCT [19]. This wavelength range is in between two water absorption peaks, and the Rayleigh scattering of the light is lower compared to light at wavelengths in the 1300–800 nm ranges that are currently used routinely for OCT applications. Devices such as a tunable AWG can be modified relatively easy to operate in this wavelength range.

In this paper, we demonstrate two different InP-based tunable filters designed to be used in a monolithically integrated tunable laser source for FD-OCT purposes. Both filters are based on the principle of a tunable AWG filter with an array of voltage-controlled PHMs in the arms of the filter array. These types of filters are chosen for three main reasons. First, the combination of these two filters can be tuned over more than 200 nm

in the 1600–1800 nm wavelength region. Second, the filters can in principle be tuned within a nanosecond due to the fast electro-optical response in the reversely biased PHMs [20]. The third reason is that these filters can be fabricated within the active/passive integration technology of COBRA [21], [22], and integrated laser systems in the required wavelength range can be realized.

The tunable filters have been realized on a single InP chip and are positioned in a monolithically integrated ring laser structure. In this way, the filter inputs are connected to quantum-dot (QD) optical amplifiers. Consequently, an on-chip 1600–1800 nm amplified spontaneous emission (ASE) light source is available that can be used to characterize the AWGs. This paper focuses entirely on the results from the tunable AWG filters. Such results are of a wider interest than just for intracavity laser applications: for example, they may be used for switching of optical signals in the wavelength domain. Two types of such filters are presented. The first configuration is the more traditional AWG design with free propagation regions (FPRs) to couple light into and out of the array of waveguides. In the second configuration, multimode interferometers (MMIs) are used for distributing and collecting the light to and from the waveguide array. To our knowledge, this is the first time this integrated MMI-based filter is presented.

First, the principle of the tunable AWG is presented in Section II. Then, the design issues of the filters are discussed in Section III; the issues relating to the new wavelength range and the fabrication limitations in Section IV. After the fabrication details in Section V, the calibration procedure and control of the tunable AWGs is presented in Section VI, and the tuning capabilities are demonstrated over the 1630–1790 nm wavelength range in Section VII. The measurement results demonstrate that the AWG operates satisfactorily thus demonstrating for the first time that the ridge waveguide InP-based optical integration technology can be applied in the 1600–1800 nm wavelength range. The results on the performance of ring laser devices using the filters will be presented elsewhere. Details on the QD amplifier material can be found in [23].

II. TUNING PRINCIPLE

In an AWG, the light entering at the input is distributed over an array of n waveguides. At the other end of the array, the output of the waveguide array is combined again. The physical path length difference ΔL between adjacent array waveguides is such that the optical pathlength difference is an integer number m times the wavelength λ_c . When the effective index of the array waveguides is N_{eff} , the central wavelength of the AWG can be expressed as [24]

$$\lambda_c = \frac{\Delta L \cdot N_{\text{eff}}}{m}. \quad (1)$$

From this equation, it can be seen that the order m of the filter can be increased to $(m+1)$ by increasing the optical pathlength difference with one wavelength without affecting the central wavelength

$$\lambda_c = \frac{\Delta L \cdot N_{\text{eff}} + \lambda_c}{m+1}. \quad (2)$$

Furthermore, we know that this increase in optical pathlength difference causes a shift in the central wavelength when the filter is treated as an m th-order filter. This shift in central wavelength is called the FSR and equals [24]

$$\Delta\lambda_{\text{FSR}} = \frac{\lambda_c}{m} \cdot \frac{N_{\text{eff}}}{N_g} \quad (3)$$

where N_g is the group index in the waveguide mode. In other words, the central wavelength of the filter λ_c can be shifted with $\Delta\lambda_{\text{FSR}}$ when the optical pathlength difference is increased with one wavelength λ_c .

The increase in optical pathlength difference can be introduced with an array of PHMs in the arms of the AWG. Including an array of PHM in the arms of the filter with an equal length L_{PHM} does not influence the filter characteristics. The optical pathlength of PHM i can be expressed as

$$S_{\text{PHMi}}^{\text{opt}} = L_{\text{PHM}} \cdot N_{\text{PHMi,eff}}. \quad (4)$$

Applying a reverse-biased voltage on PHM i increases the effective index in the waveguide [16], resulting in an increase in optical pathlength

$$\Delta S_{\text{PHMi}}^{\text{opt}}(V_i) = L_{\text{PHM}} \cdot \Delta N_{\text{PHMi,eff}}(V_i) \quad (5)$$

where $\Delta N_{\text{PHMi,eff}}(V_i)$ is the change in effective index when a reverse-biased voltage V_i is applied on PHM i . A linear increasing optical pathlength difference ΔS_{PHM} in the array of PHMs can be introduced if

$$\Delta S_{\text{PHMi}}^{\text{opt}}(V_i) = i \cdot \Delta S_{\text{PHM}} \quad \text{for } i = 1, 2, \dots, n \quad (6)$$

where $\text{PHMi} = 1$ is the innermost PHM with the shortest initial arm length. If this linear increasing optical pathlength difference ΔS_{PHM} introduced by the array of PHMs equals one wavelength λ_c , we know from the aforementioned equations that either the order m of the AWG is increased to $m+1$ or the central wavelength of the filter is shifted over one FSR $\Delta\lambda_c = \Delta\lambda_{\text{FSR}}$. When ΔS_{PHM} is a fraction of λ_c , it also shifts the central wavelength over a fraction of the FSR. The shift in central wavelength due to the introduction of ΔS_{PHM} in the PHMs can be expressed as

$$\Delta\lambda_c = \frac{\Delta S_{\text{PHM}}}{\lambda_c} \Delta\lambda_{\text{FSR}}. \quad (7)$$

This linearly increasing extra optical pathlength difference ΔS_{PHM} with respect to the central wavelength λ_c can also be expressed as an introduced extra optical phase difference $\Delta\phi$:

$$\Delta\lambda_c = \frac{\Delta\phi}{2\pi} \Delta\lambda_{\text{FSR}}. \quad (8)$$

The introduced extra optical pathlength in each of the PHMs can also be expressed as an extra introduced optical phase

$$\Delta\phi_{\text{PHMi}} = i \cdot \Delta\phi. \quad (9)$$

Before tuning the filter to a desired wavelength relative to the central wavelength λ_c , the extra optical phase difference $\Delta\phi$

has to be determined with (8). Then, the necessary extra optical phase for each PHM can be calculated with (9).

When scanning the tunable AWG over one FSR, there is one arm in the waveguide array of which the optical pathlength is not changed. This arm can be chosen to be any arm with number i_c . The other arms numbered i are then varied over an optical pathlength which is $(i - i_c) \cdot \Delta\phi$. Since only the phase is relevant for the interference at the output, the pathlength change can be limited to at most 2π phase delay. This limiting of the pathlength change does not change the transmission for the central wavelength, but does introduce a small change in the filter transmission for other wavelengths which we neglect. This small change occurs due to the fact that the AWG does not have an accurately defined order number when the extra introduced optical phases are truncated to modulo 2π . This truncation also makes it possible to choose the arm with number i_c arbitrarily because only the relative phase matters. Thus, the PHMs never have to be driven to a delay over 2π . However, this has an important technical consequence for the control. When a continuous scan is made over the FSR of the AWG, all arms except for the arm i_c and its direct neighboring arms will have to have large changes in their control voltages at the points where the 2π phase jumps occur. Together with the accuracy requirement on the phase setting, this will mean a strict requirement on the control electronics in terms of bandwidth and slew rate to be derived from the required scan speed.

III. DESIGN

The requirements on the filter are imposed by the requirements of the laser in which the filter is going to be used [25]. These requirements are that the filter should be tunable between 1600 and 1800 nm with a filter bandwidth less than 0.5 nm and a parabolic filter shape [24]. This means that for the filter, an FSR is larger than 200 nm and a full-width-half-maximum (FWHM) is less than 0.5 nm. A single AWG filter with a 0.5 nm FWHM and an FSR of 200 nm can be designed on InP; however, it requires a large AWG with more than 200 arms in the AWG. To make such a filter tunable implies that more than 200 individually controlled phase shifters should be included in the arms of the AWG. In practice, this means also more than 200 parallel voltage sources, all individually bounded to the chip. From the practical point of view, this becomes very inconvenient. Also, the size of the filter would become prohibitively large.

We chose to design two filters: the first filter is a high-resolution (HR) filter with an FWHM of 0.5 nm and an FSR of 10 nm, and the second filter is a low-resolution (LR) filter with an FWHM of 29 nm and an FSR of 210 nm. The HR filter is used as a narrow wavelength filter to allow a maximum of three ring laser cavity modes with a 0.02 nm mode spacing and suppressing other neighboring ring cavity modes. This HR filter, however, has a periodical passband response in the wavelength domain with a periodicity of the FSR, in this case approximately 10 nm. The LR filter is used to select one passband of the HR filter and suppress the other passbands. In Fig. 1, an example of usable transmission characteristics of the two filters are given.

The tunable filters presented in this paper are designed to be used for transverse electric (TE)-polarized light in the

Fig. 1. Example of filter characteristics of the HR filter (solid line) and LR filter (dashed line).

1600–1800 nm wavelength region. This optimization for TE polarization is chosen since the intended use of the filter is in a TE-polarized laser.

IV. LAYERSTACK AND WAVEGUIDE DESIGN

The filters are fabricated using the active/passive integration technology of COBRA [21], [22]. This integration technology is optimized for the 1550 nm wavelength region. However, as we will demonstrate, it can also be used in the 1600–1800 nm wavelength region without large modifications to the layerstack and the fabrication process. The standard integration technology uses a 500 nm (Q1.25) InGaAsP film layer which is not intentionally doped (n.i.d.) which in practice means slightly n-doped ($6 \times 10^{16} \text{ cm}^{-3}$) in our technology. Two types of ridge waveguides are available in our integration technology. The first is a $2.0 \mu\text{m}$ wide low-contrast waveguide where the ridge is etched 100 nm into the index guiding InGaAsP layer (shallow etch) to achieve the lowest propagation loss. The second type is a $1.5 \mu\text{m}$ wide deeply edged high-contrast waveguides for sharp bends where the etch is at least 100 nm through the index guiding layer.

Deeply etched high-contrast waveguides, which have a higher waveguide loss compared to shallow etched waveguides, are not used in the designs presented here. This was to minimize the fabrication process complexity and thus fabrication reliability. The size reductions achievable through the use of deep etched waveguide were minimal. As the second advantage, the absence of these deeply etched areas reduces height differences over the wafer which increases the wafer uniformity after polyimide planarization (which will be discussed in Section IV).

Using the same standard shallow waveguides in the 1600–1800 nm region has an influence on the waveguide performance. The absorption coefficient in InGaAsP (Q1.25) reduces due to the larger distance to the bandgap [26]. This absorption is, however, estimated to be negligible. The size of the optical mode, however, increases due to the longer wavelength. The overlap of the optical mode with the n-doped InP bottom cladding and the p-doped InP top cladding increases due to this optical mode increase. Especially, the increasing overlap with the p-doped InP top cladding introduces more losses. These losses are estimated to increase from approximately 2.7 to 4.6 dB/cm [27]. Furthermore, the increase in mode size increases the overlap with the sidewall and so the losses due to sidewall roughness. For this reason, the waveguide

Fig. 2. Layerstack and schematic cross section of the different used components. Note that the dimensions are not scaled.

width is increased from 2.0 to $2.2 \mu\text{m}$, just underneath the cutoff of the third-order mode. The waveguide losses in the 1600–1800 nm wavelength range are, therefore, expected to be only 0.2–0.6 dB/cm higher than at 1550 nm due to the increase in mode size.

The film layer as well as the 200 nm InP layer on top of the film layer is n.i.d. to reduce waveguide losses. Experiments on test structures show that the phase-shift efficiency in p-doped waveguides increases due to the increase in carrier-induced electro-optical effects; however, it also increases the losses due to the increase in free carrier absorption.

In Fig. 2, the layerstack as well as the schematic cross section of the different components is presented.

A. HR Filter

For the HR filter, we choose to use a 154th-order orthogonal shaped AWG [28], containing 28 arms with a physical arm length difference of $\Delta L = 81.16 \mu\text{m}$. The layout of this orthogonal shaped AWG has been adapted in two aspects. The first is that an array of PHMs has been added in the arms of the AWG; with these PHMs, the filter can be tuned. The second is that the waveguide layout was modified, so the PHM waveguides had a fixed $30 \mu\text{m}$ distance between them. The fixed distance ensures that the distribution of waveguides over the chip area of the PHMs is uniform. This is necessary for a step in the processing of the chip to obtain a sufficiently uniform polyimide planarization before p-metal contact evaporation. It increases the reliability of the fabrication of the electrical contacts on top of the PHMs. The adaption in the layout has been performed by tilting the vertical parts of the arms in the AWG as shown in Fig. 3(a). Keeping the innermost arm of the AWG as a reference arm, all the other arms can be placed at equal distances from each other by choosing the proper tilting angle for each arm. The AWG filter has been simulated with an S-matrix-oriented CAD-tool [29] resulting in a filter with an FWHM of 0.50 nm and a spectral suppression of 0.064 dB at 0.04 nm (two ring cavity modes with 0.02 nm mode spacing) from the central wavelength, both determined from the power spectrum.

B. LR Filter

For the LR filter, a standard AWG filter shape could not be used. The arm length differences for this seventh-order LR filter have to be only $3.69 \mu\text{m}$. In a standard AWG design [24], it is not possible to get such a small arm length difference width, the preferred $30 \mu\text{m}$ spacing between the phase shifters. For this

Fig. 3. (a) Schematic design of the HR filter. The dotted lines represent the original array arms which are moved to get equal distances between all arms. (b) S-shaped LR filter. The dotted lines represent the original array arms which are moved to introduce the small arm length differences. (c) MMI-tree-shaped LR filter. The MMI trees on both sides are tilted to introduce the small arm length differences.

Fig. 4. Simulated filter responses of an S-shaped AWG filter including 11 arms (solid) and an MMI-tree filter including eight arms (dashed). Both filters have the same arm length difference between adjacent arms.

LR filter, two different filter shapes are considered; an AWG laid out in an S-shape [2] and a filter based on an MMI-tree. The S-shaped AWG is a zero-order filter redesigned on one side to introduce the small arm length differences as schematically depicted in Fig. 3(b). In the MMI-tree-based filter, the light is distributed over the arms of the waveguide array in the filter by means of a series of 1×2 MMI couplers called an MMI-tree [see Fig. 3(c)]. The arm length differences in this layout are introduced in between the MMI-tree and the array of PHMs on both sides.

There is a difference in filter response between these two filter arrangements when an equal number of arms and equal arm lengths are used. This is mainly due to the difference in light distribution over the arms. In the S-shaped AWG, the light is distributed among the arms in the FPR. This leads to a Gaussian distribution of the light over the arms in the array which leads to a Gaussian spectral filter response. In the MMI-tree-based filter, the light is distributed equally over all the arms with the balanced 1×2 MMI couplers. This rectangular shaped distribution over the arms results in a sinc^2 response in the power spectrum.

The filter response from both LR filter types has been simulated with the CAD-tool. The S-shaped AWG filter has been simulated with 11 arms and the MMI-tree shaped filter with eight arms (three-level MMI-tree). The calculated spectral filter characteristics are given in Fig. 4. From Fig. 4, one clearly sees that the MMI-tree filter has a sharper filter response than the S-shaped AWG filter despite the lower number of arms. The penalty for the MMI-tree filter is in the spectral response outside

Fig. 5. (a) Designed waveguide and PHM mask of the complete integrated tunable laser system 10×6 mm. Also plotted is the metallization of the PHMs to indicate their position. (b) Zoom in on FPR of the HR AWG filter showing the design features to prevent back reflections and the positions of the input and output waveguides. (c) Zoom in on MMI-tree from the LR filter showing how the path length differences have been realized.

the passband. For the MMI-tree-shaped filter, the spectral suppression is more than 13 dB, whereas the spectral suppression for the S-shaped AWG filter is more than 30 dB. This difference is a direct consequence from the Gaussian and sinc^2 spectral response from the S-shaped AWG filter and the MMI-tree filter, respectively. This lower spectral suppression in the MMI-tree filter outside the passband is however no problem for the use in the ring laser. An extra suppression from 13 to 30 dB in one roundtrip does not make any difference.

More important is the suppression at approximately 10 nm from the central wavelength of the filter. This LR filter has to select one passband from the HR filter and suppress all others. From the simulations, it could be determined that the S-shaped AWG filter has a 29 nm FWHM resulting in 1.44 dB suppression at 10 nm from the central wavelength. The MMI-tree filter has a 25 nm FWHM resulting in 1.97 dB suppression at 10 nm from the central wavelength.

Based on these simulations, it was decided to use the MMI-tree filter as an LR filter in the tunable ring laser. It has a sharper filter response using less arms (also less PHM). Furthermore, the layout of the MMI-tree filter is more compact, resulting in less waveguide losses and a smaller chip area necessary. PHMs are included in the arms of the filter to make the filter tunable. These PHMs are separated with a fixed $30 \mu\text{m}$ pitch for the same reason as in the HR filter.

C. Mask Layout

In Fig. 5(a), the designed waveguide mask is presented for the complete integrated tunable laser system including the two filters. All waveguides are designed to be $2.2 \mu\text{m}$ wide ridge shallow waveguides etched 100 nm into the film layer. In the center of the mask design, the orthogonal shaped tunable AWG HR filter is located including the 28, 5 mm long PHMs. These PHM are parallel to the [0-11] crystal direction to maximize the Pockels effect providing a positive refractive index change in this direction. The linear phase-shift efficiency in these types of PHMs turned out to be in the order of $0.4 \text{ rad}/(\text{V} \cdot \text{mm})$ at 1550 nm [30] and also depends on the final doping in the waveguide. The control electronics available has a maximum output voltage

of 10 V. To keep the control voltages as low as possible and to make sure that a 2π phase shift can be obtained, 5 mm length was chosen for the PHMs.

On both sides of the AWG, multiple input and output waveguides are connected to the FPR as can be seen in Fig. 5(b). Five waveguides are equally spaced in the center of the FPR with a 1.2 nm channel spacing. The central waveguide is used as input or output in the ring laser cavity; the other four waveguides are leading to a cleaved facet and can be used as test input or output. Besides these five waveguides, two more waveguides are positioned close to the corner of the FPR. These are positioned at the higher diffraction order of the waveguide array when the zero-order image is focused on the central output waveguide. These test waveguides also lead to a cleaved facet. In between the five central waveguides and the waveguides in the corner, a triangular shaped FPR is added to prevent reflection of the ends of the FPR directly back into the AWG [see Fig. 5(b)].

Below the HR filter, the LR MMI-tree filter is located. In Fig. 5(c), one side of the filter is depicted including the MMI-tree. It clearly shows how the MMI-tree is slightly tilted on both sides with respect to the PHMs to introduce the small arm length differences.

Both filters are positioned next to each other with the PHM from both filters parallel to each other keeping the 30 μm pitch spacing in between the PHMs. In this way, a large area was created with a uniform PHM distribution to improve the polyimide planarization. For the same reason, 20 extra test/dummy PHMs and waveguides are included underneath and above the PHMs in the filters.

All input and output waveguides exit the chip at an angle of 7° with respect to the normal of the cleaved facet in order to minimize facet reflections.

V. FABRICATION

The devices were fabricated on wafers that contained active as well as passive areas to realize both active layerstack components [semiconductor optical amplifiers (SOAs)] as well as passive layerstack components (waveguides, AWGs, MMIs, and PHMs). The active-passive layerstack has been fabricated using the butt-joint integration approach [31]. The active layerstack is first grown on an n-type InP (100) substrate by metal-organic vapor-phase epitaxy, as presented in [32]. In the active region, above the 500 nm n-InP buffer layer, five InAs QD layers are stacked with an ultrathin GaAs interlayer underneath each QD layer to control the size of the QDs. These QD layers are placed in the center of a 500 nm InGaAsP n.i.d. (Q.125) optical waveguiding core layer. The QD layers are designed to produce a gain spectrum in the 1600–1800 nm wavelength region [23]. The passive areas are selectively etched back till 20 nm underneath the QD layers. In the first regrowth step, the passive InGaAsP (n.i.d. Q1.25) film layer is grown. In the second regrowth step, the common 1.5 μm p-InP top cladding is grown followed by a compositionally graded 300 nm p-InGaAs(P) top contact layer.

The devices are fabricated using a three-step $\text{CH}_4\text{-H}_2$ reactive-ion dry etch process to create shallow etched waveguides with or without contact layer and isolation section to prevent electrical crosstalk between PHMs and SOAs. The structures are planarized using six layers of polyimide. These six layers

Fig. 6. Photograph of the resulting 10 $\times$ 6 mm chip.

Fig. 7. SEM picture of a PHM waveguide cross section including the p-contact metallization and polyimide planarization.

of polyimide are necessary to increase the surface flatness of the polyimide which in this case is necessary to open all PHMs and SOAs at the same time prior to metal evaporation. For this reason, the PHMs are also equally spaced with a fixed 30 μm pitch to reduce nonuniform polyimide planarization. Height variations in the polyimide cause height variations in the opening of the PHMs and SOAs. This leads either to polyimide in between part of the PHMs and the metal when the polyimide not enough is etched away or leads to areas where too much polyimide is etched away. This leads to higher waveguide losses due to the reduced spacing between the metal and the optical mode. Furthermore, using the six layers, a thicker total layer of polyimide has to be etched away which results in a rough surface. This roughness increases the adhesion of the metal to the polyimide.

Evaporated Ti/Pt/Au metal pads contact the PHMs and SOAs to apply a voltage or a current. The SOA contact pads are thickened with plated Au to reduce the electrical resistance. The backside of the n-InP substrate is metalized to create a common ground contact.

The structures are cleaved off from the rest of the wafer and no coating is applied to the facets. A picture of the 10 $\times$ 6 mm chip is depicted in Fig. 6. A scanning electron microscope (SEM) picture of the cleaved facet of one of the PHMs is depicted in Fig. 7.

VI. MEASUREMENTS

The laser chip including the two filters is mounted p-side up on a copper chuck. This copper chuck is cooled with a constant water flow of 13° , 15 mm underneath the chip, to keep

the chip stable and at a constant temperature. The temperature of the chip is not actively controlled with a Peltier element. This is not necessary due to the constant current injection in the amplifiers and the low reverse-biased currents through the electro-optic PHMs of the tunable filters. The bond pads of the PHMs are bonded individually to a printed circuit board (PCB) which is also mounted on the copper chuck. On this PCB, each connection leads to a connector to which the electronics can be connected. This method avoids the fragile use of multiprobes directly on the chip.

Each PHM is controlled by a 13 bit arbitrary waveform generator with a voltage range between -10 and $+10$ V. (We will only use the -10 V to 0 V range) [33]. A waveform pattern can be uploaded into a 4096 word memory for each waveform generator. A common clock and a common trigger signal can be used to step through each waveform pattern for the PHMs at the same time. The minimum step size is 10 ns and settling time is 4 ns between $+0.5$ and -0.5 V (40 ns between $+5$ and -5 V). These coupled arbitrary waveform generators can be used to control all PHMs parallel with a 100 MHz rate.

All results presented here are obtained with TE light emitted by the QD SOAs. The output light from cleaved output facets is collected with a lensed fiber and measured with a spectrum analyzer with a minimum resolution of 0.05 nm (YOKOGAWA AQ6375).

First, the static filter characteristics are presented and discussed followed by a description of the PHM calibration method and the calibration results for both filters. In the second part, the tuning results of both filters are presented.

A. Static Filter Characteristics

The waveguide loss was measured at 1535 nm which is the standard wavelength at which optical losses of all our devices are measured using a Fabry–Pérot-based loss measurement technique [34]. This makes that the results can be compared with other waveguides fabricated and measured for the use around 1550 nm. The losses were determined to be (1.9 ± 0.4) dB/cm (TE) which indicates a good optical material quality and waveguide etching quality. Direct measurement of the waveguide losses around 1700 nm was not possible due to the fact that we did not have suitable single-mode tunable light sources available in that wavelength region. The waveguides losses around 1700 nm wavelength are expected to be slightly higher (extra 0.2 – 0.6 dB/cm) as discussed earlier. An estimate of the waveguide losses and the losses in the filters can be made by comparing the optical spectrum from a QD amplifier with the optical spectrum from a similar QD amplifier through a filter. The difference in peak power at the central passband wavelengths gives an indication of the total losses. This has been done for the AWG filter. The total losses were approximately 10.5 dB. These losses include the 9.2 mm passive waveguide losses outside the filter. Assuming the same waveguide loss as measured at 1535 nm, the optical loss in the AWG is 8.8 dB. To compare this value with common AWG loss figures, one must also subtract the expected loss in the 5 mm long PHM waveguides in the filter which leaves 7.8 dB. This loss value is relatively large compared to a typical excess loss value of 4 dB

in an InP AWG [35]. It indicates that the waveguide losses are slightly higher.

The first aspect to consider for the electrical characterization of the PHMs is the dark current. The dark current gives an indication on the quality and reliability of the PHM. A dark current in the nanoampere range at -10 V results in an operating current in the microampere range (dependent on the light intensity in the PHM). Higher dark current can indicate a leakage current in the PHM or the electrical circuit. This leakage current can increase during the first couple of measurements (less than ten measurements) and sometimes exceeds 50 mA at -10 V. This leads to unwanted heat generation possibly in the chip which detunes the central wavelength of the filters. In worse case, the PHM will be damaged resulting in an uncontrollable PHM.

The dark current has been measured in four 5 mm long test PHMs under reverse bias. These test PHMs are used instead of the PHMs in the filters to prevent damage to the bond pads during probe contacting. Two of these PHM show a similar V – I curve with a dark current of less than 60 nA at -10 V. The two other PHMs had a dark current of 178 nA and 1.35 μ A at -10 V indicating a leakage current. The path of the leakage current is not yet known and can only be determined by the destructive removal of the chip from the setup. So far, we only could see that the high leakage current does not directly influence the performance of the PHM. PHMs with low leakage current show comparable relation between applied voltage and resulting phase-shift efficiencies. This is an indication that the leakage path is outside the PHM.

The arbitrary waveform generators, however, cannot provide this high leakage current. This results in a nonlinear voltage drop from the voltage setting to the actual voltage on the PHM. These PHMs with a high leakage current still work as a proper PHM but will not be taken into account when the phase-shift efficiency to the PHMs is discussed.

B. Calibration Method of the PHMs

To be able to tune the filters the central wavelength(s) of the passband(s), the FSR and the electro-optical behavior of the PHMs has to be known. The electro-optical behavior of the PHMs defining the relation between the applied voltage and the optical phase shift can be expressed in a quadratic polynomial function

$$\Delta\phi_i(V_i) = aV_i^2 + bV_i + c \quad (10)$$

where a and b are the quadratic and linear phase change originating from field-induced electro-optical effects and free carrier depletion-based electro-optical effects which change the refractive index in the PHM [16]. The c term is the phase offset originating from phase errors in the arms of the filters due to variations in layer thicknesses over the wafer and fabrication imperfections. This relation between applied voltage and phase can be determined for each PHM by tuning that particular PHM_{*i*} in the AWG filter over a voltage range and measuring the optical response of the filter in a small wavelength region (a factor 2 smaller than the width of the passband of the filter). The transmitted optical power will vary when the voltage is scanned due to the constructive or destructive interference of the light from

Fig. 8. Two examples of the measured transmitted optical power versus the applied voltage and the fitted curve for the PHM in the central arm of the tunable AWG filter (circle) and for a PHM in the outmost arm of the tunable AWG filter (squares) (1680.8 nm passband used).

that particular arm i with the light in the other arms. The output power can be described according to

$$P = A + C \cdot \cos(aV_i^2 + bV_i + c). \quad (11)$$

Here, P is the measured optical power, A is the mean output power, and C is the modulation depth of the output power due to the varying phase shift in the single PHM. The coefficients a , b , and c describe the phase-shift characteristics. A voltage-dependent reduction in the modulation depth caused by an increase in absorption due to the band edge shift [20] is not observed. Also, no linear power fluctuation due to the applied voltage was observed. Both effects are therefore omitted.

The a , b , and c coefficients describing the phase-shift characteristics have been determined using an automated measurement routine. In this measurement routine, the ASE from one of the QD amplifiers is used as a light source and the transmitted optical power through one of the passbands of the filter is recorded with a 0.2 nm resolution spectrum analyzer. The measurement routine scans the voltage on a single PHM over at least 2π phase shifting (0 to -7 V in 0.1 V steps) and records the optical output power through the filter at the central wavelength of the passband. The a , b , and c terms are extracted by a least square fitting routine of (11) to the recorded data. This routine is executed on each PHM for several wavelengths as discussed later. After each routine, the PHM is set to the voltage for a zero phase shift (found by setting (10) equals 0). In Fig. 8, two examples of recorded scans in the 1680.8 nm passband are presented. The transmitted optical power is recorded versus the reverse-biased voltage on the PHM in the central arm of the AWG filter (circles) and on the PHM in the outermost arm of the AWG filter (squares). The fitted curve is also given in this figure, showing a very good agreement with the measurements.

C. Calibration of the HR Filter

The central wavelengths of the passbands in the HR filter have been determined by measuring the optical spectrum through the HR filter at one of the monitor outputs using the ASE from one of the QD-SOAs as light source. The FSR and shape of the transmission channels could be determined from this spectrum. The measured spectrum and the wavelength-dependent FSR are

Fig. 9. (a) Static optical response of the HR filter using the SOA as an ASE light source (solid). Measured FSR between two adjacent passbands (circles). (b) Zoom in on the measured central passband at 1701.2 nm (solid) and the designed filter characteristics (dashed) (compensated for a 1.2 nm shift and adjusted in power level).

given in Fig. 9(a). The envelope in the spectrum originates from the ASE spectrum of the SOA. The filter is designed to have a passband at the central wavelength of 1700 nm. This means that the monitor output has a designed passband 1.2 nm from this central wavelength, resulting in a passband at 1698.8 nm. The measured passband is located at 1701.2 nm which means a 2.4 nm spectral shift with respect to the designed value. This spectral shift originates from a difference between the effective indexes of the waveguide mode in the filter compare to the used value in the design. The measured FSR around 1700 nm corresponds to the targeted 10 nm FSR at 1700 nm within 0.04 nm. The FWHM of the passband at 1701.2 nm is 0.46 nm where 0.5 nm at 1700 nm is the design value. In Fig. 9(b), the measured central passband of the HR filter as well as the designed filter characteristics (corrected for the shift in central wavelength and the absolute power level) is given. These measurements indicate that the phase errors in the AWG arms are relatively small as will be discussed later.

Within the HR filter, 26 out of 28 PHMs were functional, and eight PHMs had a high leakage current between 10 and 50 mA, which means they have significantly different calibration parameters. The voltage of two PHMs could not be controlled due to an open circuit in the electronic circuit on the PCB. The a , b , and c coefficients have been determined at all central passband wavelengths of the HR filter between 1630 and 1800 nm for the 26 functional PHMs. The offset value c is ideally 0 rad for all PHMs at the central wavelength in a passband of the filter, and in the worst case, it varies between 0 and 2π rad (more than 2π cannot

Fig. 10. Measured phase offset values c for all 18 proper working PHMs in the HR filter. Each PHM has a different marker.

Fig. 11. Wavelength-dependent average linear phase-shift term b and the statistical error for the HR filter (diamond) and the LR filter (circle).

be discriminated from a value between 0 and 2π rad). The maximum difference between the measured c values for all PHMs at a certain wavelength gives an indication about the phase error in the arms of the filter. The measured c values for the 18 properly working PHMs in the HR filter are depicted in Fig. 10. For these PHMs, the maximum difference between the measured c values is less than 2.2 rad (at all wavelengths). Assuming that the phase error never exceeds 2π , based on the fact that the maximum difference in phase offset only varies less than 2.2 rad, indicates that the error in arm lengths due to wafer nonflatness and fabrication imperfections is less than 0.04% taking an average arm length of 10 mm in the HR filter.

The linear phase-shift term b is expected to be the same for all PHMs at the same wavelength. In Fig. 11, the average b coefficients over the 18 properly working PHMs is given including the statistical error (standard deviation divided by square root of $n-1$) in the 1630–1800 nm wavelength region. The wavelength dependence of the b coefficient is attributed to the change in optical mode size and the wavelength dependence in the electro-optical effects.

The average linear phase-shift efficiency in these PHM can be calculated from Fig. 11 and varies between 0.33 rad/V·mm at 1633 nm to 0.26 rad/V·mm at 1796 nm. The quadratic phase-shift term a was in all cases between -0.04 and $+0.04$ rad/V² (5 mm long PHM) indicating a minor influence on the phase shifting but it could not be neglected.

Fig. 12. Determined c values for each PHM in the LR filter for different wavelengths.

D. Calibration of the LR Filter

The determination of the central wavelength of the passband of the LR filter and the FSR of the filter is less straightforward than that of the HR filter. The LR filter is positioned in between two SOAs on the chip and could only be measured with one SOA as ASE light source and the other SOA used as output amplifier. The central wavelength could, however, not directly be determined from a measured spectrum due to the convolution of the ASE spectrum of the first SOA with the passband spectrum of the filter and the wavelength-dependent gain and ASE from the second SOA. Also, the FSR could not be measured directly, owing to the fact that the next passband of the filter is designed to be 210 nm away from the designed 1700 nm central passband of the filter. These passbands are far outside the ASE spectrum of the SOAs.

The phase-shift coefficients a , b , and c could be measured in the same way as in the HR filter. The difference is, however, that these coefficients are not measured at the central wavelength of the filter but at fixed chosen wavelengths resulting in an extra offset value which will be discussed later.

Within the LR filter, all PHMs were functional with one PHM having a high leakage current as discussed previously. The a , b , and c coefficients have been determined at different wavelengths between 1640 and 1780 nm. The average linear phase-shift term b including the statistical error is given in Fig. 11. The average b values correspond to the founded b values in the HR filter. The quadratic phase-shift term a was in all cases between -0.04 and $+0.04$ rad/V² as in the HR filter.

During the calibration, each calibrated PHM is tuned to its zero-phase position ($\Delta\phi_i(V_i) = aV_i^2 + bV_i + c = 0$) after its calibration. This tunes the filter toward the calibration wavelength. Since the coefficients are now also determined at wavelengths in between the LR filter transmission maxima, the offset values c are to be interpreted somewhat different from those determined at the passbands of the HR filter. The c values are equal to the phases needed to compensate the linear increasing/decreasing phase change necessary to tune the filter away from the static central wavelength. By analyzing the c values found, it is possible to calculate back the static central wavelength and the FSR of the filter. In Fig. 12, the c values that have been determined using the PHM calibration method described earlier are given for the LR filter at different wavelengths. For the c values at each

Fig. 13. Wavelength-dependent slopes of the determined c values over the PHMs and a linear fit to determine the FSR.

wavelength, it is possible to determine a slope (rad/PHM). This represents the linear increasing/decreasing phase change $\Delta\phi$ (8) necessary to tune the filter to that wavelength. The slopes that have been found for each wavelength are presented in Fig. 13. For the central wavelength of the filter, it is known that the c values are ideally all 0 rad which means $\Delta\phi = 0$. In Fig. 13, the wavelength for which $\Delta\phi = 0$ indicates the central wavelength of the filter and it was determined to be 1726.6 nm. Furthermore, it is known that the filter is tuned over one FSR if $\Delta\phi = 2\pi$. With a linear fit (neglecting the wavelength dependence of the FSR) on the datapoints in Fig. 13, it was possible to estimate the FSR and it was found to be 220 nm.

VII. TUNING RESULTS

When the wavelength-dependent phase-shift coefficients are determined for each PHM as well as the central wavelength(s) of the passband(s) and the wavelength-dependent FSR, all information is available for the filters to be tuned in a predictable way. The tuning is always performed relative to the nearest calibration point (for the HR filter, the passband wavelengths and for the LR filter, the chosen calibration wavelengths). The extra optical phase $\Delta\phi$ can then be determined with (8) using a linear fitted value of the wavelength-dependent FSR $\Delta\lambda_{\text{FSR}}(\lambda)$. (The 2π modulus of this phase can be used.) The voltage necessary for each PHM to realize the required phase change in each PHM can be calculated with (10) using the calibrated coefficients for each PHM.

A. HR Filter

In Fig. 14, the spectrum between 1685 and 1715 nm is given for the HR filter using the ASE from one of the SOAs as a light source. This 30 nm bandwidth covers three FSR resulting in three passbands within this spectrum. The filter is tuned from 1700 nm (solid) toward 1698 nm (dashed) and 1696 nm (dotted). All passbands of the filter shift together with respect to the FSR of the filter. In this case, $\Delta\phi = -(2/5)\pi$ for tuning from 1700 to 1698 nm and $\Delta\phi = -(4/5)\pi$ for tuning from 1700 to 1696 nm.

The performance of the filter is determined by the undesired detuning of the filter with respect to the target wavelength and the FWHM of the filter. These quantities have been measured over 160 nm between 1630 and 1790 nm in 0.1 nm steps while tuning the HR filter over this wavelength region and using the

Fig. 14. Spectral response HR filter for three tuning wavelengths: 1700 nm (solid), 1698 nm (dashed), and 1696 nm (dotted).

Fig. 15. Tuning accuracy HR filter between 1630 and 1790 nm. The measured central wavelength of the selected passband is given with respect to the target wavelength (dashed) as well as the FWHM of the passband (black solid) and the detuning of the central wavelength (gray solid).

ASE from the SOA as a light source. The measured central wavelength of the used passband and the FWHM of the passband are recorded. In Fig. 15, the measured central wavelength as well as the detuning with respect to the target wavelength and the FWHM of the passband is given. It can be seen from Fig. 15 that the filter can be tuned in a predictable way over the full 160 nm with an accuracy of ± 0.1 nm (1% of the FSR) and an FWHM between 0.4 and 0.5 nm. The detuning presented in Fig. 15 shows a periodical behavior with a periodicity of the FSR of the filter. This indicates a small error (approximately 1%) in the determination of $\Delta\phi$. This error is most probably from neglecting wavelength dependence (λ_{FSR} and b_i) within one FSR.

The calibration of the PHMs and the response of the tunable filter over time is very stable. We did not observe any notable change in the filter tuning performance after using the filter with the same calibration data for four months.

B. LR Filter

The LR filter is again less straightforward to characterize. The spectral response has been measured using the ASE from one SOA as light source which is sent through the LR filter and afterward amplified by the second SOA. To minimize spectral deformation, this second SOA has been biased around threshold. Due to the wavelength-dependent gain in the SOA [23], this spectral

Fig. 16. Spectral response LR filter for three tuning wavelengths: 1700 (solid black), 1720 (black dotted), and 1740 nm (solid gray).

Fig. 17. Tuning accuracy of the LR filter between 1670 and 1770 nm. The measured central wavelength of the passband is given with respect to the target wavelength (solid black) as well as the FWHM of the passband (squares) and the detuning of the central wavelength (gray dots).

deformation could not completely be prevented. The transmission spectrum through the filter was corrected for the ASE spectrum from the second SOA. The signal from the second SOA was measured with the first SOA switched OFF, and this spectrum was then subtracted from the spectrum with both SOAs switched ON. In Fig. 16, the resulting spectra are presented for three tuning wavelengths 1700, 1720, and 1740 nm of the LR filter. (Note that the ASE from the output SOA is dependent on the input signal and more intense without input signal. Subtracting this spectrum thus resulted in a negative power spectrum.) The performance of the filter has been measured between 1670 and 1770 nm by measuring the detuning and the FWHM of the spectra. The detuning is defined as the difference between the peak wavelength in the spectrum and target wavelength. The FWHM is measured at half the intensity difference between the peak wavelength and the lowest valley in the spectrum. It can be seen from Fig. 17 that the LR filter can be tuned in a predictable way with an accuracy of ± 9 nm (4% of the FSR) at the edge of the spectrum and less than ± 6 nm (2.7% of the FSR) in the central part of the spectrum. This measured tuning accuracy is influenced by the ASE spectrum of the input SOA which moves the measured filter transmission peak toward the peak of the ASE spectrum. This effect is the cause of the slope in the measured detuning. The FWHM fluctuates between 15 and 27 nm where 25 nm was designed. This narrowing of the measured FWHM

is due to the nonuniform input spectrum and the spectral deformation in the output amplifier. The filter transmission of the HR filter and LR filter could not be measured in cascade due to their integration in a ring laser structure. The performance of the ring laser, including the two filters will be published elsewhere.

C. Filter Tuning Speed

To get a clear indication of the tuning speed of the filters, a measurement was made of the time-dependent transmitted optical power from an external laser through the HR filter when switching the filter between two wavelengths. Due to the fact that we did not have a suitable external light source available in the 1700 nm wavelength region and the ASE from the QD amplifier was not strong enough, we performed this switching measurement with an external single-mode laser at 1597.9 nm. The 1597.9 nm is chosen because this wavelength is at a higher order passband of the HR filter when the filter is tuned to 1700 nm. The laser light is coupled into a monitor output of the HR filter with a lensed fiber and collected with another lensed fiber from a monitor output at the other side of the HR filter. The transmitted light was detected with an amplified photodetector with 3 ns rise time. The filter is switched between 1700 and 1745 nm to pass or reject the 1597.9 nm laser light through the filter. The 10–90% rise and fall time are measured to be 100 and 80 ns, respectively. These values are significantly longer than the response time of a single PHM in a Mach–Zehnder interferometer of less than 1 ns [20]. The measured 100 ns response time is, therefore, limited by the electronics. First of all, there is a limitation in the control electronics which has a limited rise time determined by the slew rate of 0.25 V/ns. Since the largest voltage swing in the switching of the wavelength is approximately 4 V, this means approximately 16 ns switching time. Apparently, the additional capacities of cabling (1 m) and in the PCB are the main reason for the lower than expected switching speed.

VIII. CONCLUSION

In this paper, we have presented two monolithically integrated electro-optically tunable filters in the 1700 nm wavelength region. The filters are designed to be used in a monolithically integrated tunable laser source in this wavelength region. The filters have been fabricated within a QD active/passive InAs/InGaAsP/InP integration technology used at COBRA. We demonstrate that this integration technology, designed for the use at 1550 nm wavelength, can also be used successfully in the 1600–1800 nm wavelength region without a large penalty in performance.

The HR filter is an AWG filter with 5 mm long PHMs in the 28 arms of the AWG. The LR filter consists of an MMI-tree-based filter with 5 mm long PHM in eight arms of the filter. To our knowledge, this is the first time such an MMI-tree-based filter has been used. The phase-shift efficiency of the PHM has been determined for a wide wavelength region between 1630 and 1800 nm. The linear phase-shift efficiency is found to be wavelength dependent and varying between 0.33 rad/V·mm at 1633 nm to 0.26 rad/V·mm at 1796 nm. A quadratic term in the phase-shift efficiency was observed but this only had a minor influence on the voltage to phase relation in the PHMs. The phase offset was determined to be less than 2.2 μm in all waveguides,

indicating an error in the optical length of the arms of less than 0.04%.

Both filters could be tuned in a predictable way. The HR filter was demonstrated to be tunable over 160 nm from 1630 to 1790 nm with an accuracy of ± 0.1 nm (1% of the FSR) and an FWHM between 0.4 and 0.5 nm. The LR filter was demonstrated to be tunable over 100 nm from 1670 to 1770 nm with an accuracy of ± 9 nm (4% of the FSR) and an FWHM between 15 and 27 nm. These tuning range demonstrations were limited by the ASE from the QD amplifiers used as a light source at 1700 nm. In principle, the filters can be tuned over a larger wavelength region.

Both filters satisfy the requirements for the filters to be used in the integrated tunable laser source.

REFERENCES

- [1] L. A. Coldren, "Monolithic tunable diode lasers," *IEEE J. Sel. Topics Quantum Electron.*, vol. 6, no. 6, pp. 988–999, Nov. 2000.
- [2] T. Tanemura, M. Takenaka, A. Al Amin, K. Takeda, T. Shioda, M. Sugiyama, and Y. Nakano, "InP-InGaAsP integrated 1×5 optical switch using arrayed phase shifters," *IEEE Photon. Technol. Lett.*, vol. 20, no. 12, pp. 1063–1065, Jun. 2008.
- [3] A. F. Fercher, W. Drexler, C. K. Hitzenberger, and T. Lasser, "Optical coherence tomography—Principles and applications," *Rep. Prog. Phys.*, vol. 66, no. 2, pp. 239–303, Jan. 2003.
- [4] T. Zimmermann, J. Rietdorf, and R. Pepperkok, "Spectral imaging and its applications in live cell microscopy," *FEBS Lett.*, vol. 546, no. 1, pp. 87–92, Jul. 2003.
- [5] P. Werle, "A review of recent advances in semiconductor laser based gas monitors," *Spectrochimica Acta A*, vol. 54, no. 2, pp. 197–236, Feb. 1998.
- [6] A. D. Kersey, M. A. Davis, H. J. Patrick, M. LeBlanc, K. P. Koo, C. G. Askins, M. A. Putnam, and E. J. Friebele, "Fiber grating sensors," *J. Lightw. Technol.*, vol. 15, no. 8, pp. 1442–1463, Aug. 1997.
- [7] M. S. Nawrocka, T. Liu, X. Wang, and R. R. Panepucci, "Tunable silicon microring resonator with wide free spectral range," *Appl. Phys. Lett.*, vol. 89, no. 7, pp. 071110–1–071110–3, Aug. 2006.
- [8] D. H. P. Maat, F. H. Groen, R. C. Horsten, Y. C. Zhu, P. E. W. Kruis, C. G. P. Herben, X. J. M. Leijtens, and M. K. Smit, "Tunable phased array demultiplexer on InP featuring wide-range tuning and pass-band shaping," presented at the 9th Eur. Conf. Integr. Opt., Torino, Italy, Apr. 1999, Postdeadline Papers.
- [9] A. Q. Liu and X. M. Zhang, "A review of MEMS external-cavity tunable lasers," *J. Micromech. Microeng.*, vol. 17, no. 1, pp. R1–R13, Dec. 2006.
- [10] A. J. Ward, D. J. Robbins, G. Busico, E. Barton, L. Ponnampalam, J. P. Duck, N. D. Whitbread, P. J. Williams, D. C. J. Reid, A. C. Carter, and M. J. Wale, "Widely tunable DS-DBR laser width monolithically integrated SOA: Design and performance," *IEEE J. Sel. Topics Quantum Electron.*, vol. 11, no. 1, pp. 149–156, Jan. 2005.
- [11] H. Bukkems, "New approaches to widely tunable semiconductor lasers," Ph.D. dissertation, Technische Universiteit Eindhoven, Eindhoven, The Netherlands, 2006.
- [12] J. H. den Besten, R. G. Broeke, M. van Geemert, J. J. M. Binsma, F. Heinrichsdorff, T. van Dongen, E. A. J. M. Bente, X. J. M. Leijtens, and M. K. Smit, "An integrated coupled-cavity 16-wavelength digitally tunable laser," *IEEE Photon. Technol. Lett.*, vol. 14, no. 12, pp. 1653–1655, Dec. 2002, (with correction: vol. 15 p. 353, Feb. 2003).
- [13] C. R. Doerr, C. H. Joyner, and L. W. Stulz, "40-wavelength rapidly digitally tunable laser," *IEEE Photon. Technol. Lett.*, vol. 11, no. 11, pp. 1348–1350, Nov. 1999.
- [14] M. J. R. Heck, P. Munoz, B. W. Tilma, E. A. J. M. Bente, Y. Barbarin, Y. S. Oei, R. Nötzel, and M. K. Smit, "Design, fabrication and characterization of an InP-based tunable integrated optical pulse shaper," *IEEE J. Quantum Electron.*, vol. 44, no. 4, pp. 370–277, Apr. 2008.
- [15] E. A. J. M. Bente, Y. Barbarin, J. H. den Besten, M. K. Smit, and J. J. M. Binsma, "Wavelength selection in an integrated multiwavelength ring laser," *IEEE J. Quantum Electron.*, vol. 40, no. 9, pp. 1208–1216, Sep. 2004.
- [16] J.-F. Vinchant, J. A. Cavaillès, M. Erman, P. Jarry, and M. Renaud, "InP/GaInAsP guided-wave phase modulators based on carrier-induced effects: Theory and experiment," *J. Lightw. Technol.*, vol. 10, no. 1, pp. 63–69, Jan. 1992.
- [17] J. H. den Besten, "Integration of multiwavelength lasers with fast electro-optical modulators," Ph.D. dissertation, Technische Universiteit Eindhoven, Eindhoven, The Netherlands, 2004.
- [18] L. Zhang, J. Sinsky, D. van Thourhout, N. Sauer, L. Stulz, A. Adamiecki, and S. Chandrasekhar, "Low-voltage high-speed travelling wave InGaAsP-InP phase modulator," *IEEE J. Photon. Technol. Lett.*, vol. 17, no. 8, pp. 1831–1833, Aug. 2004.
- [19] V. M. Kodach, J. Kalkman, D. J. Faber, and T. G. van Leeuwen, "Quantitative comparison of the OCT imaging depth at 1300 nm and 1600 nm," *Biomed. Opt. Exp.*, vol. 1, no. 1, pp. 176–185, Jul. 2010.
- [20] L. Xu, "Monolithic integrated reflective transceiver in indium phosphide," Ph.D. dissertation, Technische Universiteit Eindhoven, Eindhoven, The Netherlands, 2009.
- [21] M. K. Smit, R. Baets, and M. Wale, "InP-based photonic integration: Learning from CMOS," presented at the 35th Eur. Conf. Opt. Comm., Vienna, Austria, Sep. 20–24, 2009.
- [22] E. A. J. M. Bente and M. K. Smit, "Ultrafast InP optical integrated circuits," presented at the SPIE Proc. 6124 Optoelectron. Integr. Circuits VIII, San Jose, CA, 2006.
- [23] B. W. Tilma, M. S. Tahvili, J. Kotani, R. Nötzel, M. K. Smit, and E. A. J. M. Bente, "Measurement and analysis of optical gain spectra in 1.6 to 1.8 μm InAs/InP (100) quantum-dot amplifiers," *Opt. Quantum Electron.*, vol. 41, no. 10, pp. 735–749, May 2010.
- [24] M. K. Smit and C. van Dam, "PHASAR-based WDM-devices: Principles, design and applications," *IEEE J. Sel. Topics Quantum Electron.*, vol. 2, no. 2, pp. 236–250, Jun. 1996.
- [25] B. W. Tilma, E. A. J. M. Bente, X. J. M. Leijtens, R. N. Nötzel, and M. K. Smit, "Design of an integrated electro-optically tunable filter for tunable laser purposes," in *Proc. 14th Eur. Conf. Int. Opt.*, Eindhoven, The Netherlands, Jun. 2008, pp. 181–184.
- [26] F. Fiedler and A. Schlachetski, "Optical parameters of InP-based waveguides," *Solid-State Electron.*, vol. 30, no. 1, pp. 73–83, Jan. 1987.
- [27] J. P. Weber, "Optimization of the carrier-induced effective index change in InGaSP waveguides application to tunable Bragg filters," *IEEE J. Quantum Electron.*, vol. 30, no. 8, pp. 1801–1816, Aug. 1994.
- [28] H. Takahashi, I. Nishi, and Y. Hibino, "10 GHz spacing optical frequency division multiplexer based on arrayed-waveguide grating," *Electron. Lett.*, vol. 28, no. 4, pp. 380–382, Feb. 1992.
- [29] X. J. M. Leijtens, P. Le Lourec, and M. K. Smit, "S-matrix oriented CAD-tool for simulating complex integrated optical circuits," *IEEE J. Sel. Topics Quantum Electron.*, vol. 2, no. 2, pp. 257–262, Jun. 1996.
- [30] L. Xu, X. J. M. Leijtens, T. de Vries, Y. S. Oei, P. J. van Veldhoven, R. Nötzel, and M. K. Smit, "Efficient deeply etched InP/InGaAsP phase shifters with low dark current," in *Proc. IEEE/LEOS Symp. Benelux Chapter 2007*, Brussels, Belgium, Dec. 2007, pp. 115–118.
- [31] J. J. M. Binsma, M. van Geemert, F. Heinrichsdorff, T. van Dongen, R. G. Broeke, and M. K. Smit, "MOVPE waveguide regrowth in InGaAsP/InP with extremely low butt joint loss," in *Proc. IEEE/LEOS Symp. Benelux Chapter 2001*, Brussels, Belgium, Dec. 2001, pp. 245–248.
- [32] S. Anantathanasarn, R. Nötzel, P. J. van Veldhoven, F. W. M. van Otten, Y. Barbarin, G. Servanton, T. de Vries, B. Smalbrugge, E. J. Geluk, T. J. Eijkemans, E. A. J. M. Bente, Y. S. Oei, M. K. Smit, and J. H. Wolter, "Lasing of wavelength-tunable (1.55 μm region) InAs/InGaAsP/InP (100) quantum dots grown by metal organic vapor-phase epitaxy," *Appl. Phys. Lett.*, vol. 89, no. 7, pp. 073116–1–073116–3, 2006.
- [33] TUEDACS TU/e Data Acquisition & Control System—AWG100 2009. [Online]. Available: www.tuedacs.nl
- [34] R. G. Walker, "Simple and accurate loss measurement technique for semiconductor optical waveguides," *Electron. Lett.*, vol. 21, no. 13, pp. 581–583, Jun. 1985.
- [35] J. H. den Besten, M. P. Dessens, C. G. P. Herben, X. J. M. Leijtens, F. H. Groen, M. R. Leys, and M. K. Smit, "Low-loss. Compact, and polarization independent PHASAR demultiplexer fabricated by using a double-etch process," *IEEE Photon. Technol. Lett.*, vol. 14, no. 1, pp. 62–64, Jan. 2002.

Bauke W. Tilma (S'05) received the M.Sc. degree in electrical engineering from the Eindhoven University of Technology, Eindhoven, The Netherlands, in 2006, and the Ph.D. degree from the Photonic Integration Group (formerly Opto-Electronic Devices Group), COBRA Research Institute, Eindhoven University of Technology, in 2011. His thesis research was focused on the full temporal magnitude and phase characterization of picoseconds laser pulses using spectral interference at the Opto-Electronic Devices Group of the Eindhoven University of Technology. His dissertation research was focused on a monolithically integrated tunable quantum-dot laser source for optical coherence tomography in the 1.7 μm wavelength region.

Since summer 2011, he has been a Postdoctoral Researcher at the Eidgenössische Technische Hochschule, Zürich, Switzerland, where he is involved in the research on electrically pumped vertical external cavity surface-emitting lasers and modelocked integrated external-cavity surface-emitting lasers and their modelocking.

Yuqing Jiao (S'09) received the B.Eng. degree from the Department of Optical Engineering, Zhejiang University, Hangzhou, China, in 2008, where he currently working toward the Ph.D. degree. He has also been working toward the exchange Ph.D. degree in the Photonic Integration Group (formerly Opto-Electronic Devices Group), the COBRA Research Institute, Eindhoven University of Technology, Eindhoven, The Netherlands, since 2010, where he is involved in the research on InP-based laser system and photodetector for optical coherence tomography in the 1.7 μm wavelength region.

Peter J. van Veldhoven received the Bachelor of chemistry degree, with the differentiation process technology, in 1989.

He then joined Philips Research labs to work on ferroelectric epitaxial oxide layers grown by metal-organic vapor phase epitaxy (MOVPE) for nonvolatile memories. When the FERAM project was finished, he worked on the development of silicon technology for the integration of nonvolatile memory options in standard CMOS processing. In 1998, he left Philips Research and joined Philips FABWAG operations where he did product yield engineering on charged-coupled device image sensors and double poly bipolar transistors for cellular phone applications. In 2002, he joined JDS Uniphase as a Process Engineer for MOVPE of III/V layers for long wavelength laser applications. When JDS Uniphase closed down part of their operations in Eindhoven, The Netherlands, in 2002, he went to the Eindhoven University of Technology, Eindhoven, where he has been working on the growth of III/V materials in the Group Photonics and Semiconductor Nanophysics.

Barry Smalbrugge received the M.Sc. degree in solid-state chemistry and inorganic chemistry from the Catholic University of Nijmegen (now Radboud University), Nijmegen, The Netherlands, in 1983, focused on electroabsorption measurements at the indirect edge of silicon, and electrochemical methods.

In 1986, he joined the Opto-Electronic Devices Group, Eindhoven University of Technology, Eindhoven, The Netherlands, where he is currently involved in back-end processing within III/V Semiconductor Technology: wet-chemical etching, electrodeposition, scribing/cleaving, and wire bonding.

Huib P. M. M. Ambrosius received the Ph.D. degree in chemistry from the Catholic University of Nijmegen (now Radboud University), Nijmegen, The Netherlands, in 1981.

He then joined Philips Research Labs in Eindhoven, The Netherlands, where he was involved in research on III/V technology for lasers and photodetectors. From September 1987 to September 1988, he was an Expat at the Philips Research Lab in Limeille-Brevannes, France, focused on the first planetary metal-organic vapor phase epitaxy reactor. After the acquisition of the Philips Optoelectronic Center by Uniphase (later JDS Uniphase) in 1998, he was an Engineering Manager in the Waferfab until JDS Uniphase closed down the facility in Eindhoven in 2004. In 2005, he co-founded Cedova BV in Eindhoven, and in 2009 he joined the Optoelectronic Devices Group, Eindhoven University of Technology, Eindhoven, as the Director Clean Room and as such responsible for the clean room activities and the technology of the Optoelectronic Devices Group.

Peter J. Thijs, biography not available at the time of publication.

Xaveer J. M. Leijtens (M'00) received the M.Sc. (Hons.) and Ph.D. degrees in physics from the University of Amsterdam, Amsterdam, The Netherlands, in 1988 and 1993, respectively.

He then joined the Photonic Integrated Circuits Group at TU Delft. Since 2000, he has with the COBRA research center, Eindhoven University of Technology, Eindhoven, The Netherlands. He is the author or coauthor of more than 150 papers and conference contributions and three book chapters. His research interests include generic photonic integration and he is leading the design effort within the Joint European InP platform, JePPIX.eu.

Dr. Leijtens is a member of the Board of the IEEE Photonics Society Benelux Chapter and was the Chairman of the Board from 2005 to 2008. Since 2007, he has been an Associate Editor of the IEEE PHOTONICS TECHNOLOGY LETTERS.

Richard Nötzel received the Diploma degree in physics from the Technical University of Munich, Munich, Germany, in 1989, and the Ph.D. degree in semiconductor physics from the University of Stuttgart, Stuttgart, Germany, in 1992.

During 1993, he was with Nippon Telegraph and Telephone (NTT) Corporation, Atsugi, Japan. During 1994, he was a Visiting Associate Professor, and later, a Visiting Professor at Hokkaido University, Sapporo, Japan. In 1995, he was with Paul Drude Institute for Solid State Electronics, Berlin, Germany. Since 2000, he has been an Associate Professor at Eindhoven University of Technology, Eindhoven, The Netherlands. His current research interests include direct synthesis of low-dimensional semiconductors and their electronic properties for applications in novel photonic devices, and integrated circuits.

R. Nötzel was the recipient of the Berlin-Brandenburg Academy Award for Science, NTT Opto-Electronics Laboratories Award, and Otto Hahn Medal of the Max-Planck Society.

Meint K. Smit (F'03) received the M.Sc. (Hons.) and Ph.D. (Hons.) degrees in electrical engineering from Delft University of Technology, Delft, The Netherlands, in 1974 and 1991, respectively.

He started research in integrated optics in 1981. He was closely involved in the development of the multimode interference coupler. Since 2000, he has been the Leader of the Photonic Integration Group, COBRA Research Institute, Eindhoven University of Technology, Eindhoven, The Netherlands. His current research interests include InP-based Photonic Integration, including integration of InP circuitry on Silicon.

Dr. Smit is a Fellow of the IEEE Photonics Society. He received a LEOS Technical Achievement Award in 1997 for the invention of the Arrayed Waveguide Grating.

Erwin A. J. M. Bente (M'01) received the Ph.D. degree from the Vrije Universiteit, Amsterdam, The Netherlands, in 1989, on atomic laser spectroscopy.

He has been an Associate Professor at the Eindhoven University of Technology, Eindhoven, The Netherlands, since 2001. He is involved in integrated Indium-phosphide-based tunable and short pulse laser systems. From 1988 to 2001, he has worked in industry on laser isotope separation and at the Vrije Universiteit and the Institute of Photonics, University of Strathclyde, Glasgow, U.K., on solid-state laser development and nonlinear optics.