Optimisation of optical bandpass filters for all-optical wavelength conversion using genetic algorithms

Citation for published version (APA):

Molina Vázquez, J., Li, Z., Liu, Y., Tangdiongga, E., Zhang, S., Lenstra, D., Khoe, G. D., & Dorren, H. J. S. (2007). Optimisation of optical bandpass filters for all-optical wavelength conversion using genetic algorithms. *IEEE Journal of Quantum Electronics*, 24(1), 57-64. <https://doi.org/10.1109/JQE.2006.884741>

DOI:

[10.1109/JQE.2006.884741](https://doi.org/10.1109/JQE.2006.884741)

Document status and date:

Published: 01/01/2007

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.

Optimization of Optical Band-Pass Filters for All-Optical Wavelength Conversion Using Genetic Algorithms

J. Molina Vázquez, *Member, IEEE*, Z. Li, Y. Liu, *Member, IEEE*, E. Tangdionga, S. Zhang, D. Lenstra, *Senior Member, IEEE*, G. D. Khoe, *Fellow, IEEE*, and H. J. S. Dorren, *Member, IEEE*

Abstract—We propose using genetic algorithms to numerically optimize optical band-pass filters (OBFs) for inverted and noninverted wavelength conversion based on semiconductor optical amplifiers. A fourth order Hermite–Gaussian sum series is used to describe the filter transfer function. Signal eye openings greater than 30 dB are obtained for both inverted and noninverted output signals. The dependence of the eye opening, overshoot and pulse amplitude fluctuation on variations in the filter center frequency and bandwidth is explored. We find that for an optimized eye opening in the noninverted signal the filter should be detuned towards lower frequency with respect to the probe frequency. Finally, we show that the optimum filter transfer function obtained with the genetic algorithm can be approximated with good agreement using an asymmetric Mach–Zehnder interferometer combined with a Gaussian OBF.

Index Terms—Genetic algorithms, optical band-pass filters (OBFs), semiconductor optical amplifiers (SOAs), wavelength conversion.

I. INTRODUCTION

WAVELENGTH conversion has been investigated extensively in the past several years as it will play an important role in future wavelength division multiplexing optical networks [1]. Wavelength conversion techniques based on semiconductor optical amplifiers (SOA), promising due to their large nonlinearities and potential for integration, have attracted considerable attention [2]. However, relatively long carrier lifetimes (typically tens to hundreds of picoseconds) result in significant pattern effects limiting the maximum pattern-effect-free bit rate.

Different approaches have been proposed to reduce the pattern effects in high-speed SOA-based wavelength converters [3]–[6] demonstrating operation speeds as high as 320 Gbit/s. All these similar techniques can be generalized as a structure composed of a SOA followed by an optical filter, which has been investigated by different groups [7], [8]. The filter transfer

Fig. 1. SOA-based wavelength conversion with OBF.

function is critical in determining the output signal quality and, to the best of our knowledge, it is unknown which is the optimum filter transfer function that can produce large output signal eye openings with reduced overshoot or pulse amplitude fluctuations.

In this paper we propose the use of genetic algorithms to optimize the filter transfer function used for inverted and noninverted wavelength conversion. We investigate the effect of variations in the filter center frequency and bandwidth on the output signal quality and show that the optimum filter can be implemented experimentally using an asymmetric Mach–Zehnder interferometer combined with a Gaussian optical band-pass filter (OBF). We find output signal eye openings greater than 30 dB for both inverted and noninverted outputs and the latter is more robust against variations in the filter transfer function.

The paper is organized as follows. In Section II, we briefly introduce the model and method used in our simulations and the criteria used to evaluate the filters during the optimization. The optimization results are given in Section III followed by a comparison between the optimum filter and the AMZI plus OBF approximation to the optimum filter in Section IV. Finally, our results are discussed in Section V and an overall summary is given in Section VI.

II. SIMULATION AND OPTIMIZATION

We first model SOA-based wavelength conversion at 160 Gbit/s using the setup shown in Fig. 1 and use the output from this model as the input to the genetic algorithm (GA) filter optimization. Note that, during the optimization of the filters, the SOA output, which is the input to the GA, does not change.

The filter following the SOA in Fig. 1 converts the chirp dynamics experienced by the probe signal during copropagation in the SOA with a modulated pump signal into amplitude modulation. This can be exploited to perform ultrafast wavelength conversion since the chirp dynamics evolve within the pump pulse duration [7], [9]. If one replaces the continuous-wave probe with a clock pulse at subrate, this setup can be used for demultiplexing as in [10], where the output is inverted.

Manuscript received May 10, 2006; revised July 27, 2006. This work was supported in part by the Netherlands Organization for Scientific Research (NWO) and in part by the Technology Foundation STW through a NRC Photonics Grant and the VIDI Programme.

J. M. Vázquez, Z. Li, Y. Liu, E. Tangdionga, S. Zhang, G. D. Khoe, and H. J. S. Dorren are with the COBRA Research Institute, Eindhoven University of Technology, Eindhoven 5600 MB, The Netherlands (e-mail: j.molina.vazquez@ieee.org).

D. Lenstra is with the Department of Electrical Engineering, Mathematics, and Computer Engineering, Delft University of Technology, 2628 CD Delft, The Netherlands.

Color versions of Figs. 1–6 and 10 are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/JQE.2006.884741

A. Wavelength Conversion

An extended bulk SOA rate equation model [11] is used to simulate wavelength conversion at 160 Gbit/s. The model includes ultrafast carrier dynamics such as spectral hole burning, two photon absorption and carrier heating. In addition, gain dispersion and group velocity dispersion are also taken into account in a similar fashion as that in [12]. A finite-difference beam propagation method (FD-BPM) [12] is adopted to integrate the electrical field equation. The SOA has a strained bulk active region length of 250 μm and an active volume of 50 μm^3 . Further details of the SOA model can be found in [11]. The calculations are performed for 160 mA injection current. The model has shown good agreement with experimental results when it was used to simulate the gain recovery dynamics [9].

Following an initial stabilization process of the SOA, 64 bits from a pseudorandom bit sequence of length $2^7 - 1$ are used to generate pump pulses at 1566 nm wavelength with 5 fJ input energy and 1.5-ps duration, which are then wavelength converted onto a continuous wave probe at 1550-nm wavelength with 10 mW input power. The output from the SOA, which is composed of the pump and probe light combined, is then used as the input to the filter optimization algorithm.

B. Genetic Algorithms

For a given signal spectrum $E_s(\nu)$, the ideal filter transfer function $T(\nu)$ can be obtained by dividing the signal spectrum by the spectrum of the desired ideal signal $E_0(\nu)$ [7], i.e.,

$$T(\nu) = E_s(\nu)/E_0(\nu). \quad (1)$$

However, one can see that such a filter only gives the desired ideal results for the given signal E_s . Since any other signal would have a different spectrum, one would need a different filter for each converted signal, which is unsuitable for real time telecommunications applications. In this paper, we aim to find a single optimum filter that is suitable for different converted signals. To do this, we propose the use of a GA to optimize the filter transfer function for SOA-based wavelength conversion, and therefore the output signal.

GAs are a multiparameter optimization technique used in evolutionary computing, inspired by Darwin's theory of evolution, to solve problems by an evolutionary process resulting in a best solution [13], [14]. An initial population is randomly created consisting of a number of individuals where each individual is composed of several chromosomes. The chromosomes are composed of a binary sequence and represent the different parameters that are to be optimized. Each individual is then evaluated based on given criteria and given a fitness score. Based on this fitness score, the strongest individuals are selected for mating and the weaker ones die off and are removed from the population. During the mating, there is an exchange of different parts of the binary sequence composing the parent individuals and there is also the possibility that a mutation occurs. The mating continues until the population reaches its original size and then the whole selection procedure is repeated. Repeating the selection and reproduction processes leads to the evolution of the population and eventually, after sufficiently long time, to the best solution. The main advantage of using GAs over other optimization techniques is their ability

to avoid local solutions and find good solutions quickly even for difficult search spaces. They are very well suited for nonlinear problems and can manipulate many parameters simultaneously. Finally, the searching mechanism is intrinsically parallel and does not require information about the path taken to arrive at a given point. Hence, GAs can sample the solution space in multiple directions and find solutions that may otherwise be ignored as they may not be in the current search path [13].

To optimize the filter transfer function we use a common GA technique with a population size of 100 individuals, and a probability of jump mutation, cross-over and creep mutation of 0.02, 0.5, and 0.04, respectively. The difference between the jump and creep mutations is that in the former a parameter, represented by a chromosome, can take any random value within the parameter range whereas in the latter a chromosome also takes a random value but which is, in this case, only one increment away from its parent value [13], [14]. In both cases, the mutated chromosome is different to the parents' corresponding chromosome. The combination of a Gaussian and Hermite sum series gives freedom to the GA to generate a band-pass filter with a sufficiently arbitrary shape. Hence, a fourth-order Hermite-Gaussian sum series given by

$$T(\nu) = \exp \left[-\frac{(\nu - \delta\nu)^2}{2\Delta\nu^2} \right] \sum_{i=0}^4 a_i H_i \left(\frac{\nu - \delta\nu}{\Delta\nu} \right) \quad (2)$$

describes the filter transfer function $T(\nu)$, where ν is the frequency and H_i is the i th order Hermite polynomial with coefficient a_i . For simplicity, we refer to $\delta\nu$ ($\delta\nu = \nu_f - \nu_{\text{probe}}$) and $\Delta\nu$ as the filter center frequency detuning (relative to the probe frequency ν_{probe}) and bandwidth, respectively. However, the Hermite polynomial series may cause the actual center frequency and bandwidth of the filter to differ. Since it is possible to approximate a filter with a linear phase response to a given amplitude response [15], we assume a linear phase response, which simply causes a delay in the signal. A nonlinear phase response would cause the output signal to drift in time and distinguishing 0 and 1 bits becomes nontrivial. The GA is used to optimize the filter center frequency, bandwidth and a_i coefficients, represented by the chromosomes; and therefore the filter's amplitude transfer function, to give maximum eye opening and minimum overshoot (pulse amplitude fluctuation) for the inverted (noninverted) signal, i.e., the fitness evaluation criteria.

C. Filter Evaluation

For the inverted signal, we define the eye opening (EO) as the logarithm of the minimum ratio between the inverted zero power level and the inverted one power level, i.e.,

$$\text{EO} = 10 \log_{10} \left[\frac{P_{\min}^0}{\max(P_{\min}^1)} \right] \text{ dB} \quad (3)$$

and the overshoot (OS) as

$$\text{OS} = 10 \log_{10} \left[\frac{\min(P_{\max}^1) - \overline{P^0}}{\overline{P^0}} \right] \text{ dB}. \quad (4)$$

The OS corresponds to the portion of the inverted signal with a power level that is higher than the inverted zero level.

For the noninverted signal the eye opening is given by the logarithm of the minimum ratio between the noninverted one power level and the noninverted zero power level, i.e.,

$$EO = 10 \log_{10} \left[\frac{\min(P_{\max}^1)}{P_{\max}^0} \right] \text{ dB}, \quad (5)$$

and the pulse amplitude fluctuation is given by the standard deviation of the maxima of the 1 bits, i.e.,

$$PAF = \frac{\sqrt{\sum (P_{\max}^1 - \bar{P}_{\max}^1)^2}}{(\sqrt{N} \bar{P}_{\max}^1)} \quad (6)$$

where N is the total number of 1 bits and the sum is over all 1 bits. In (3)–(6), $\bar{P}$ is the average power, the 0 (1) superscript indicates a 0 (1) bit, the “min” (“max”) subscript indicates the minimum (maximum) power level of a particular bit, and the “min()” [“max()”] operator gives the minimum (maximum) value of a particular power level. The PAF are also known as pattern effects and are caused by the amplifier’s gain not recovering fully before the arrival of each pulse.

To evaluate the fitness of a given individual, we calculate the the fitness function

$$\mathcal{F} = C_{EO} \frac{EO}{EO_{\max}} + C_{OS} \frac{OS}{OS_{\min}} \quad (7)$$

for inverted output, and

$$\mathcal{F} = C_{EO} \frac{EO}{EO_{\max}} + C_{PAF} \frac{PAF_{\min}}{PAF} \quad (8)$$

for noninverted output. In (7) and (8), C_{EO} , C_{OS} , and C_{PAF} are weight factors that are used to give the EO, OS, and PAF, respectively, different importance. We scan over the full range of weight factors, i.e., between zero and one in steps of 0.05 with $C_{EO} + C_{OS} = 1$ and $C_{EO} + C_{PAF} = 1$, to determine which values make the GA evolve to give the best EO, OS, and PAF. $EO_{\max}$, $OS_{\min}$, and $PAF_{\min}$ are normalization coefficients used to ensure that EO, OS, and PAF have comparable orders of magnitude. These are obtained by allowing the GA to evolve to give maximum EO regardless of the value of OS or PAF, or minimum OS or PAF regardless of the value of EO.

D. Implementation Feasibility

Finally, to determine the feasibility of implementing the optimum filter experimentally, we approximate the amplitude transfer function of an asymmetric Mach–Zehnder interferometer (AMZI), which has a delay in one arm and a phase bias in the other, combined with a Gaussian OBF, which is given by

$$T_A(\nu) = \frac{1}{2} \exp \left[-\frac{(\nu - \delta\nu)^2}{2\Delta\nu^2} \right] [\exp(i\phi) + \exp(i2\pi\tau\nu)] \quad (9)$$

Fig. 2. Evolution of the best filter amplitude transfer function, at different generations where the filter improves, for an inverted output signal.

to the optimum filter transfer function obtained with the GA by changing the delay τ and the phase bias ϕ in the AMZI, and the center frequency $\delta\nu$ and bandwidth $\Delta\nu$ of the OBF. In fact, such a set-up has been used to perform regenerative all-optical wavelength conversion at 160 Gbit/s [5], [9], [16].

Note that the phase response of the AMZI is staircase-like, i.e., it is linear with a periodic π -phase drop at every point of minimum transmission, which is similar to the ideal phase response found in [7]. However, as will be seen later, the filtered output signal spectrum remains within two such minimum transmission points and, therefore, this π -phase jump does not affect the output signal. This is consistent with [8] where it is found that suppressing one of the sidebands leads to a filter equalizer function that is independent of the filter phase response. Hence, we believe that our linear phase response approximation remains valid.

III. OPTIMIZATION RESULTS

The results of the optimum filter transfer functions for inverted and noninverted output signals obtained using the GA are given in this section. First, we show details of the evolution of the population and then we investigate the output signal quality, based on the EO, OS, and PAF; dependence on changes in the filter center frequency and bandwidth.

A. Filter Evolution

Figs. 2 and 3 show the evolution of the best filter in the population at different generations for inverted and noninverted output signals, respectively. The filter spectra shown in the figures are relative to the input probe wavelength of 1550 nm as indicated. For clarity, only the most significant best filters of those generations at which there is an improvement of the best filter are shown. As the optimum filter evolves the transfer functions become very similar making them difficult distinguish. Full details of the best filter coefficients’ evolution can be obtained from Tables I and II in the appendix. One can see that initially, while the filter transfer function is far from optimal,

Fig. 3. Evolution of the best filter amplitude transfer function, at different generations where the filter improves, for a noninverted output signal.

TABLE I
FILTER COEFFICIENTS' EVOLUTION FOR INVERTED OUTPUT

#	a_0	a_1	a_2	a_3	a_4	$\delta\nu$	$\Delta\nu$
1	3.46	-4.62	-3.21	4.86	-6.83	0.332	0.189
4	4.48	-16.7	12.8	8.61	12.8	0.476	0.215
5	-2.14	-16.9	2.45	15.4	0.828	0.490	0.166
6	-6.00	12.3	13.4	13.7	-7.19	0.482	0.255
9	-14.7	9.35	9.00	-1.57	-18.4	-0.288	0.125
23	-2.88	15.8	-18.6	9.99	13.3	0.496	0.244
47	-7.81	1.69	-13.5	15.7	19.6	0.477	0.220
135	-14.6	1.37	-11.1	15.9	19.6	0.482	0.225
154	-12.1	1.29	-3.68	15.8	19.4	0.482	0.225
276	-17.0	11.5	-10.6	18.3	19.4	0.482	0.224
351	-17.0	10.2	-17.7	18.3	19.4	0.480	0.222
671	-9.38	16.1	-18.0	17.8	19.5	0.478	0.222
866	16.5	16.6	-19.3	15.3	19.5	0.482	0.222

the filter can change considerably from one improvement to the next. However, as the population evolves there is less room for improvement and the changes observed are minor adjustments to the filter transfer function. This can be interpreted as an initial coarse tuning of the filter over short periods of time with a subsequent fine tuning over long periods of time. This can also be seen from Fig. 4 where the evolution of the EO and

TABLE II
FILTER COEFFICIENTS' EVOLUTION FOR NONINVERTED OUTPUT

#	a_0	a_1	a_2	a_3	a_4	$\delta\nu$	$\Delta\nu$
1	15.5	-9.71	9.81	0.279	10.0	-0.495	0.173
3	-5.14	-3.99	4.52	-1.73	10.3	0.475	0.168
6	-2.98	6.53	-14.8	11.2	14.0	-0.467	0.167
8	7.08	18.9	19.5	5.30	18.7	-0.488	0.174
9	7.15	16.5	12.3	6.51	15.9	-0.494	0.193
17	9.51	11.5	0.721	6.51	10.9	-0.493	0.180
31	-12.8	19.7	-10.0	7.53	17.0	-0.495	0.190
32	3.58	-7.22	1.92	1.35	10.7	-0.493	0.193
33	19.7	-16.0	10.7	1.55	12.5	-0.496	0.185
44	9.59	18.6	0.451	8.35	15.2	-0.496	0.187
62	8.64	7.85	1.28	5.68	16.5	-0.499	0.187
70	7.47	-11.5	-20.0	5.85	19.0	-0.500	0.188
78	9.92	-4.56	-19.3	6.01	7.58	-0.499	0.191
89	17.4	-1.55	-18.4	7.47	2.95	-0.498	0.181
93	9.90	-1.55	-18.7	6.23	3.58	-0.496	0.190
130	9.26	-1.75	-18.6	5.92	3.74	-0.496	0.190
157	17.6	-4.72	-14.3	5.88	2.41	-0.497	0.183
299	17.8	-4.79	-14.3	5.90	2.49	-0.497	0.186
335	16.6	-3.23	-19.2	7.06	3.41	-0.497	0.187
397	19.0	-8.43	-19.2	5.53	-2.19	-0.499	0.194
729	19.0	-8.43	-19.2	5.49	-2.21	-0.499	0.194
980	19.9	-8.73	-19.2	5.61	-2.22	-0.499	0.193

OS (PAF) for the inverted (noninverted) output signal is given. These are obtained using the best filter at a particular generation where the filter improves. Interestingly, the coarse tuning of the filter is, in both cases, complete after only nine generations. However, the fine tuning process for the noninverted output signal has more intermediate steps than for the inverted output. It is important to note that already in the first generation, filters with good performance are generated. This is due to the large population used, which ensures fast convergence towards the optimum solution as can be seen from the quick completion of the coarse tuning. It is worth continuing to fine tune after this stage since EO improvements of more than 8 dB can be achieved for both the inverted and noninverted output signals.

B. Optimum Filters

Fig. 5 shows the optimized filters for the inverted and noninverted signals together with the signal spectrum before and after the filter. For the inverted signal the filter is detuned by $\delta\nu = 0.481$ THz (-3.84 nm) and has a bandwidth of 0.222 THz (1.78 nm). For the noninverted signal the filter is detuned by $\delta\nu = -0.499$ THz (4.01 nm) and has a bandwidth of 0.193 THz (1.55 nm). An important feature to note is that for the inverted output, the dip in the corresponding filter's transfer function is detuned from the probe, whereas for noninverted output the dip coincides with the probe suppressing it considerably. This agrees with the ideal filters found in [7].

Fig. 6 is used to compare the GA-optimized filters with the best filter in the first generation, which is randomly generated, and a simple Gaussian band-pass filter. The corresponding eye diagrams for the inverted and noninverted signals after propagating through the filters in Fig. 6 are shown in Fig. 7. Using the GA-optimized filter, the inverted signal EO can be improved

Fig. 4. (a) Evolution of the EO (circles) and OS (squares) for the inverted output signal. (b) Evolution of the EO (circles) and PAF (squares) for the non-inverted output signal.

Fig. 5. (a) Optimized filters for the inverted (solid) and noninverted (dashed) output signals. Also shown is the signal spectrum prior to the filter. (b) Signal spectra after propagating through the optimized filters for the inverted and non-inverted output.

considerably from 0.488 dB [Fig. 7(c)] to 31.1 dB [Fig. 7(a)], at the expense of introducing a 2.47 dB overshoot [Fig. 7(a)]. We found, by giving different weight factors to the EO and OS, that the GA evolves to either a maximum EO or a minimum OS and that an intermediate solution offering a large EO with low OS was not possible. We give the EO more importance and therefore only show the results for the optimized EO. For Fig. 7(a), weight factors of 0.95 and 0.05 for the EO and OS, respectively, were used. Similarly, we found that the PAF of the noninverted signal did not change considerably regardless of the weighting factors used. However, using the GA-optimized filter it is possible to remove the sub-pulse obtained with the Gaussian band-pass filter, with which it could only be removed using very narrow bandwidth and large detuning resulting in an output peak power lower than $5 \mu\text{W}$. The EO is improved from 9.63 dB [Fig. 7(f)] to 33.1 dB [Fig. 7(d)] and the PAF degrades from 0.0357 [Fig. 7(f)] to 0.0414 [Fig. 7(d)] with weight factors of 0.35 and 0.65 for the EO and PAF, respectively. Different weight factors could be used to obtain a better PAF but the decrease in EO was considerably larger than the PAF improvement.

Fig. 6. (a) Inverted and (b) noninverted GA-optimized filters (solid), first generation filters (dashed), and Gaussian band-pass filters (dotted).

Fig. 7. (a)–(c) Inverted and (d)–(f) noninverted eye diagrams of the wavelength converted signal after propagating through the (a), (d) optimized filter, (b), (e) first generation filter, and (c), (f) Gaussian filter.

C. Filter Tolerance

We investigate the effect on the output signal EO, OS and PAF due to variations in the optimum filters' center frequency and bandwidth to determine the flexibility and tolerance in the fabrication and utilization of the filter.

It is interesting to note in Fig. 5 that the filters' center frequency for the inverted and noninverted signals are detuned from the probe's center frequency in opposite directions. Fig. 8 shows how the EO, OS and PAF change as a function of the filters' detuning. One can see that for both the inverted and noninverted signals, there are two peaks of maximum EO almost symmetrically around the probe signal frequency. The difference in modulation depth of the chirp dynamics [7], [9] results in this slight asymmetry. For the noninverted signal the peak at higher frequency is wider than that at lower frequency, which is consistent with experiments [4], [9] where a filter detuned towards high frequency gives less PAF and it is also easier to obtain a large EO. However, this is not optimum for EO. We find that detuning towards lower frequency [~ -0.50 THz (4.13 nm)] offers a larger EO with similar PAF. If PAF is given a larger weight factor the optimum filter is then detuned towards higher frequency. For -0.45 THz (3.73 nm) $< \delta\nu$ and $\delta\nu > 0.55$ THz (-4.28 nm) in Fig. 8(a), and -0.20 THz (1.72 nm) $< \delta\nu < 0.50$ THz (-3.88 nm) in Fig. 8(b), the signal changes

Fig. 8. Filter detuning dependence of the (a) inverted EO (solid) and OS (dashed), and (b) noninverted EO (solid) and PAF (dashed).

Fig. 9. Filter frequency bandwidth dependence of the (a) inverted EO (solid) and OS (dashed), and (b) noninverted EO (solid) and PAF (dashed).

from being inverted to noninverted and vice-versa, respectively, making it difficult to define the EO, OS, and PAF.

Fig. 9 shows the dependence of the EO, OS, and PAF on the filter bandwidth. The inverted signal's quality is strongly dependent on the filter bandwidth since the EO decreases rapidly away from the optimum bandwidth. For the noninverted signal the EO decreases slowly, in particular, for larger bandwidths. For bandwidths $\Delta\nu \geq 0.4$ THz (3.23 nm), the filter is sufficiently broad to allow part of the pump signal to interfere with the probe and the converted output signal is significantly distorted. The inverted signal changes to being noninverted when the filter bandwidth $\Delta\nu < 0.2$ THz (1.60 nm). These results and those on Fig. 8 show that the noninverted signal is less sensitive to changes in the filter center frequency and bandwidth.

Finally, we tested the optimized filters using a different bit sequence such that the signal spectrum prior to the filter is different. In this case we found that the change in EO, OS, and PAF was negligible.

IV. AMZI PLUS GAUSSIAN FILTER

Having found optimum filters for inverted and noninverted output signals we now approximate the amplitude transfer function of the filters using a known experimental setup, i.e., combining an AMZI and an OBF. Fig. 10 shows the filter transfer functions for the optimum filters obtained with the GA together with those for the AMZI and OBF filter. One

Fig. 10. Filter transfer functions for the optimum GA filter (solid) and AMZI combined with OBF filter (dashed) for the (a) inverted and (b) noninverted output signals. The insets show a zoom of the region near the probe wavelength.

can see that it is possible to approximate the AMZI plus OBF filter transfer function to that of the optimum GA filter with good agreement, in particular, near the probe wavelength. In addition, the output spectra in Fig. 5 are to one side of the dip in the corresponding filter. Hence, the π -phase jump in an AMZI filter's phase response, which occurs at the dip, is not significant. For the inverted output signal, the AMZI has a phase bias $\phi = 0.710\pi$ and delay $\tau = 0.886$ ps. For the noninverted output signal, the overall approximation is not as good as the AMZI plus OBF filter transfer function deviates from the optimum GA filter away from the probe, especially for longer wavelengths. In this case, the AMZI delay is $\tau = 0.502$ ps and the phase bias is $\phi = 1.007\pi$. In both cases, the OBF has the same center frequency and bandwidth as the Gaussian function in the corresponding GA-optimized filter. Using the AMZI and OBF filter, one obtains an EO of 31.0 dB and an OS of 2.48 dB for the inverted signal, and an EO of 31.7 dB and a PAF of 0.0412 for the noninverted signal.

The sensitivity of the AMZI plus OBF filter with respect to changes in the center frequency and bandwidth is similar to the results shown in Figs. 8 and 9, respectively, for the GA-optimized filter. The filter for inverted output signal is very sensitive to variations in the phase and shows a qualitatively similar behaviour of the EO and OS as that shown in Fig. 9(a). The delay, on the other hand, can vary over a range of ~ 0.44 ps with a reduction of 3 dB in the EO and an increase of 0.5 dB in the OS. The AMZI plus OBF filter for noninverted output signal is significantly less sensitive to changes in the phase and the delay. The former can be tuned over a range of $\sim 0.020\pi$ and the delay over a range of ~ 0.77 ps for a 3 dB reduction in EO. In both cases, the variation in PAF is very small and changes only by less than 6.0%. These ranges may be increased with rather tedious adjustments of combinations of the delay, phase, center frequency and bandwidth. However, we found that the improvement in the range, over independent adjustments of the variables, was minimal.

V. DISCUSSION

When using GAs, one would ideally allow the population to evolve for an infinite number of generations to have the certainty that the best overall solution has been obtained rather than a local optimum solution. However this is not practical and one has to decide when to stop the evolution of the population. The evolution of the filters' center frequency, bandwidth and a_i coefficients (see Tables I and II in the Appendix) suggests that the filter transfer function for the inverted output may still improve with further evolution of the population. On the other hand, one can see from Figs. 2–4 that further evolution of the filter results in minor adjustments away from the probe wavelength giving small improvements in the EO and OS. Hence, we believe that allowing the population to evolve further would not result in significant modifications nor improvements of the filter amplitude transfer function.

Due to the relatively slow gain recovery in SOAs, one may expect the eye diagrams to be partially closed at the bit rate considered [7]. However, using an OBF one can exploit the ultrafast chirp dynamics to give the large eye openings shown in Fig. 7.

One can see from Fig. 6 that the filter optimization occurs at the expense of output signal power due to the large detuning of the OBF from the probe. Hence, the output signal is subject to noise. This can be overcome to give an error-free output, at the expense of reduced optical signal-to-noise ratio, by amplifying the output signal at the optimized OBF output and then filtering the noise [9].

The delays obtained for the AMZI are shorter than the pulse duration, contrary to what is used in [8]. However, this results in a small differential phase between the signals in the two arms of the AMZI. As a result, the relationship between the phase bias and the output signal's polarity (inverted or noninverted) agrees with the analytic approximation derived in [8], i.e., $\phi < \pi$ gives an inverted output and $\phi > \pi$ a noninverted signal.

Finally, one can achieve improved EO for the noninverted output by detuning the filter further away from the probe towards longer wavelengths. In doing so, one is essentially collecting more light from the pump signal and the output signal is distorted due to interference effects. In addition, the process of wavelength conversion becomes meaningless since one has input and output signals at the same wavelength. Hence, to avoid interference with the pump light and four wave mixing components, we restrict the allowed center frequency and bandwidth range that the GA may scan to $-0.5 \text{ THz} < \delta\nu < 0.5 \text{ THz}$ ($-4.01 \text{ nm} < \delta\lambda < 4.01 \text{ nm}$) and $0.1 \text{ THz} < \Delta\nu < 0.5 \text{ THz}$ ($0.801 \text{ nm} < \Delta\lambda < 4.01 \text{ nm}$).

VI. CONCLUSION

We used GAs to optimize numerically the filter transfer function used in inverted and noninverted wavelength conversion. We explored the dependence of the signal quality on variations in the filter center frequency and bandwidth and found that the noninverted signal quality was less sensitive to variations in the filter properties. In this case, the filter, optimized for maximum EO, was detuned from the probe signal towards lower frequency. Furthermore, we found eye openings greater than 30 dB for the inverted and noninverted signals and the latter was more

robust to variations in the filter's transfer function. For the inverted signal, the overshoot could not be removed without reducing the eye opening significantly. Finally, we showed that the optimum filters obtained with the GA can be approximated with good agreement using an AMZI combined with an OBF.

APPENDIX

The evolution of the center frequency (in terahertz), bandwidth (in terahertz) and coefficients of the Hermite–Gaussian sum series that describes the filter transfer function is given in Tables I and II for reference. Note that the variable values are only given for a generation where an improvement of the filter transfer function has been achieved.

ACKNOWLEDGMENT

The authors would like to thank D. L. Carroll for providing the genetic algorithm driver code.

REFERENCES

- [1] C. Nuzman, J. Leuthold, R. Ryf, S. Chandrasekhar, C. Giles, and D. Neilson, "Design and implementation of wavelength-flexible network nodes," *J. Lightw. Technol.*, vol. 21, no. 3, pp. 648–663, Mar. 2003.
- [2] S. J. B. Yoo, "Wavelength conversion technologies for wdm network applications," *J. Lightw. Technol.*, vol. 14, no. 6, pp. 955–966, Jun. 1996.
- [3] K. Tajima, "All-optical switch with switch-off time unrestricted by carrier lifetime," *Jpn. J. Appl. Phys.*, vol. 32, pp. L1726–L1749, 1993.
- [4] H. Y. Yu, D. Mahgerefteh, P. S. Cho, and J. Goldhar, "Optimization of the frequency response of a semiconductor optical amplifier wavelength converter using a fiber bragg grating," *J. Lightw. Technol.*, vol. 17, no. 2, pp. 308–315, Feb. 1999.
- [5] S. Nakamura, Y. Ueno, and K. Tajima, "168-Gb/s all-optical wavelength conversion with a symmetric-mach-zehnder-type switch," *IEEE Photon. Technol. Lett.*, vol. 13, no. 10, pp. 1091–1093, Oct. 2001.
- [6] Y. Liu, E. Tangdiongga, Z. Li, H. de Waardt, A. Koonen, G. D. Khoe, H. J. S. Dorren, X. Shu, and I. Bennion, "Error-free 320 Gb/s SOA-based wavelength conversion using optical filtering," presented at the Opt. Fiber Commun. Conf., 2006, PDP28.
- [7] J. Leuthold, D. M. Marom, S. Cabot, J. J. Jaques, R. Ryf, and C. R. Giles, "All-optical wavelength conversion using a pulse reformatting optical filter," *J. Lightw. Technol.*, vol. 22, no. 1, pp. 186–192, Jan. 2004.
- [8] M. L. Nielsen and J. Mørk, "Increasing the modulation bandwidth of semiconductor-optical-amplifier-based switches by using optical filtering," *J. Opt. Soc. Amer. B*, vol. 21, pp. 1606–1619, 2004.
- [9] Y. Liu, E. Tangdiongga, Z. Li, S. Zhang, H. de Waardt, G. D. Khoe, and H. J. S. Dorren, "Error-free all-optical wavelength conversion at 160 Gb/s using a semiconductor optical amplifier and an optical band-pass filter," *J. Lightw. Technol.*, vol. 24, no. 1, pp. 230–236, Jan. 2006.
- [10] E. Tangdiongga, Y. Liu, H. de Waardt, G. Khoe, and H. Dorren, "320-to-40-Gb/s demultiplexing using a single SOA assisted by an optical filter," *IEEE Photon. Technol. Lett.*, vol. 18, no. 8, pp. 908–910, Apr. 2006.
- [11] X. Yang, D. Lenstra, G. D. Khoe, and H. J. S. Dorren, "Nonlinear polarization rotation induced by ultrashort optical pulses in a semiconductor optical amplifier," *Opt. Commun.*, vol. 223, pp. 169–179, 2003.
- [12] N. Das, Y. Yamayoshi, and K. Kuwakiuchi, "Analysis of basic four-wave-mixing characteristics in a semiconductor optical amplifier by the finite-difference beam propagation method," *IEEE J. Quantum Electron.*, vol. 36, no. 10, pp. 1184–1192, Oct. 2000.
- [13] D. E. Goldberg, *Genetic Algorithms in Search, Optimization and Machine Learning*. Amsterdam: Addison-Wesley, 1989.
- [14] G. Yang, L. E. Reinstein, S. Pai, Z. Xu, and D. L. Carroll, "A new genetic algorithm technique in optimization of permanent ¹²⁵I prostate implants," *Med. Phys.*, vol. 25, pp. 2308–2315, 1998.
- [15] C. K. Madsen and J. H. Zhao, *Optical Filter Design and Analysis: A Signal Processing Approach*, 1st ed. New York: Wiley, 1999.

- [16] J. Leuthold, L. Möller, J. Jaques, S. Cabot, L. Zhang, P. Bernasconi, M. Cappuzzo, L. Gomez, E. Laskowski, E. Chen, A. Wong-Foy, and A. Griffin, "160 Gb/s SOA all-optical wavelength converter and assessment of its regenerative properties," *Electron. Lett.*, vol. 40, pp. 554–555, 2004.

J. Molina Vázquez (M'05) was born in Santa Cruz de Tenerife, Spain, in 1979. He received the M.Phys. degree in optoelectronics and laser engineering and the Ph.D. degree from Heriot-Watt University, Edinburgh, U.K., in 2001 and 2006, respectively.

He is presently working on ultrafast all-optical signal processing at Eindhoven University of Technology, Eindhoven, The Netherlands.

Z. Li was born in Sichuan, China, in 1979. He received the B.Sc. degree in optoelectronics and the M.Sc. degree in optics engineering from the University of Electronic Science and Technology of China, Chengdu, China, in 2000 and 2003, respectively. He is currently working toward the Ph.D. degree at Eindhoven University of Technology, Eindhoven, The Netherlands, where he is involved in research on all-optical signal processing by employing semiconductor optical amplifier nonlinearities.

Y. Liu (M'01) was born in Sichuan, China, in 1970. He received the M.S. degree from the University of Electronic Science and Technology of China, Chengdu, China, in April 1994, and the Ph.D. degree from Eindhoven University of Technology, Eindhoven, The Netherlands, in October 2004.

From 1994 to April 2000, he worked at University of Electronic Science and Technology of China. In April 2000, he joined the COBRA Research Institute at Eindhoven University of Technology. Currently, he is a Postdoctoral Researcher. His research topic is all-optical signal processing in optical cross-connects.

In 2003, Dr. Liu was awarded an IEEE Lasers & Electro-Optics Society Graduate Student Fellowship.

E. Tangdionga received the M.Sc. degree in electrical engineering in 1994 and the Ph.D. degree in optical communication in 2001, both from Eindhoven University of Technology, Eindhoven, The Netherlands.

In 1996 he joined COBRA Research Institute, Eindhoven University of Technology, where he conducted an experimental research on the topic of interferometric crosstalk in multiwavelength optical cross-connects. The work was carried out in two subsequent European Advanced Communication Technologies and Services (ACTS) projects: AC065 BLISS (Broadband LIghtwave Sources and Systems) and AC332 APEX (Advanced Photonics Experimental X-connect). In 2001–2003, he participated in the European program of Information Society Technologies (IST) project FASHION (ultraFAst Switching in High-speed Optical time-division multiplexed Networks) for realization of 160 Gbit/s all-optical add-drop switching and all-optical 10 and 40 GHz subharmonic clock recovery. He is currently working as a Senior Scientist in the same institute, responsible for realization of subpicosecond optical pulses and ultrafast all-optical demultiplexing for terabit per second data rates.

S. Zhang was born in Liaoning, China, in 1977. He received the M.Sc. degree in optical engineering from the University of Electronic Science and Technology of China, Chengdu, China, in 2002. He is currently working toward the Ph.D. degree at Eindhoven University of Technology, Eindhoven, The Netherlands.

His research interests are in laser dynamics, optical memories, and optical digital systems.

D. Lenstra (M'97–SM'06) was born in Amsterdam, The Netherlands, in 1947. He received the M.Sc. degree in theoretical physics from the University of Groningen, Groningen, The Netherlands, and the Ph.D. degree from Delft University of Technology, Delft, The Netherlands. His thesis work was on polarization effects in gas lasers.

Since 1979, he researched topics in quantum electronics, laser physics, and condensed matter physics. In 1991, he joined the Vrije Universiteit, Amsterdam, The Netherlands, holding a chair in theoretical quantum electronics. In 2000, he also became a part-time Professor at the Department of Electrical Engineering, Eindhoven University of Technology, Eindhoven, The Netherlands, where he presently occupies a chair on ultrafast photonics as a part-time Professor. His research themes are nonlinear and ultrafast dynamics of semiconductor optical amplifiers and diode lasers. He is the Scientific Director of the COBRA Research Institute, Eindhoven University of Technology, since 2005. He (co)authored more than 270 publications in international scientific journals and (co)edited 6 books and several special journal issues. He acts regularly as program (co)chair for international meetings.

Dr. Lenstra is a member of IEEE LEOS, OSA, and EPS.

G. D. Khoe (M'71–SM'85–F'91) was born in Magelang, Indonesia, in 1946. He received the degree of Elektrotechnisch Ingenieur (*cum laude*) from the Eindhoven University of Technology, Eindhoven, The Netherlands, in 1971.

He decided to start research at the Dutch Foundation for Fundamental Research on Matter (FOM) Laboratory on Plasma Physics, Rijnhuizen, The Netherlands. In 1973, he moved to the Philips Research Laboratories to start research in the area of optical fiber communication systems. In 1983, he was appointed as a part-time Professor at Eindhoven University of Technology. He became a full Professor in 1994 and is currently chairman of the Department of Telecommunication Technology and Electromagnetics (TTE). Most of his work has been devoted to single-mode fiber systems and components. Currently, his research programs are centered on ultrafast all-optical signal processing, high capacity transport systems, and systems in the environment of the users. He has more than 40 U.S. patents and has authored and co-authored more than 150 papers, invited papers, and chapters in books. His professional activities include many conferences, where he has served in technical committees, management committees, and advisory committees as a member or chairman. He has been involved in journal activities, as Associate Editor, as a Member of the Advisory Board or as Reviewer. In Europe, he is closely involved in Research Programs of the European Community and in Dutch national research programs, as participant, evaluator, auditor, program committee member, and as member of the steering committee. He is one of the founders of the Dutch COBRA University Research Institute. In 2001, he brought 4 European groups together to start a new international alliance called the European Institute on Telecommunication Technologies (eITT).

Dr. Khoe is one of the three recipients of the prestigious "Top Research Institute Photonics" grant that is awarded to COBRA in 1998 by the Netherlands Ministry of Education, Culture and Science. He has served in the IEEE/LEOS organization as European Representative in the BoG, VP Finance & Administration, VP Membership, BoG Elected Member, President and member of the Executive Committee of the IEEE Benelux Section. He was founder of the LEOS Benelux Chapter. He has been an OSA Fellow since 2006 and received the MOC/GRIN award in 1997.

H. J. S. Dorren (M'04) received the M.Sc. degree in theoretical physics and the Ph.D. degree from Utrecht University, Utrecht, The Netherlands, in 1991 and 1995, respectively.

After postdoctoral positions, he joined Eindhoven University of Technology, Eindhoven, The Netherlands, in 1996, where he presently serves as an Associate Professor. In 2002, he was also a Visiting Researcher at the National Institute of Industrial Science and Technology (AIST), Tsukuba, Japan. His research interests include optical packet switching, digital optical signal processing, and ultrafast photonics.

Dr. Dorren currently serves as an Associate Editor for the IEEE JOURNAL OF QUANTUM ELECTRONICS.