# Design and Optimization of a 1.3/1.55-$\mu$m Wavelength Selective p-i-n Photodiode Based on Multimode Diluted Waveguide

Vincent Magnin, Louis Giraudet, Joseph Harari, and Didier Decoster

***Abstract*—This letter demonstrates a new solution to achieve low-cost, highly integrated, and reliable InP-based p-i-n photodiodes for wavelength-division-multiplexing optical networks, absorbing 1.55-$\mu$m wavelength and transparent to 1.3 $\mu$m. It is based on a multimode diluted waveguide (MDW) combined with an evanescently coupled photodiode. The overall structure is optimized using a genetic algorithm linked to a beam propagation method software. The computed responsivity of the MDW photodiode is 0.86 A/W at 1.55 $\mu$m, and the 1.3/1.55-$\mu$m optical crosstalk is better than −20 dB (−40-dB electrical). The proposed device is designed for hybridization on silicon platform for low-cost modules, with potential application up to 10 Gb/s.**

***Index Terms*—Evanescent coupling, multimode waveguides, optical network, p-i-n photodiodes, wavelength-division multiplexing, wavelength selective.**

## I. Introduction

IN SOME optical-fiber-based communication systems, especially in optical access networks, a wavelength selective photodetector is mandatory to handle up-links and down-links. In particular, a low-cost photodetector, sensitive to 1.55 $\mu$m but not to 1.3 $\mu$m, would ease the realization of 1.3–1.5-$\mu$m transceivers. This cannot be achieved using a simple 1.4-$\mu$m bandgap wavelength absorbent material (GaInAsP or AlGaInAs for example). This would result in a photodiode sensitive to 1.3 $\mu$m and transparent at 1.55 $\mu$m [1]. To absorb 1.55 $\mu$m while rejecting 1.3 $\mu$m, several solutions have been proposed so far, such as p-i-n photodiodes with wavelength selective couplers or wavelength-division-multiplexing filters [2], or top-illuminated resonant-cavity photodiodes [3]. One can also absorb the 1.3-$\mu$m wavelength before it reaches the active region, with a material transparent to 1.55 $\mu$m [4].

This letter proposes a new and highly compact design for low-cost and reliable photodiodes, absorbing 1.55 $\mu$m and transparent to 1.3 $\mu$m. It is based on previous works demonstrating the interest of multimode diluted waveguides (MDW) combined with evanescently coupled photodiodes [5], [6]. MDW are made of alternate thin layers with a high optical index, here GaInAsP, and thicker layers with a lower optical index, namely InP. Their multimode properties can be utilized to achieve various functions, as for example MDW p-i-n photodiodes with high responsivity, high reliability, and high alignment tolerance at both 1.3 and 1.55 $\mu$m [5]. Reference [6] shows how MDW p-i-n photodiodes could also be tailored to absorb selectively transverse-electric (TE) or transverse-magnetic (TM) modes. All these devices, very compact, are to be hybridized on silicon platform. Such complex structure design, due to numerous geometric and material parameters, and multimode behavior, was possible thanks to a genetic optimization algorithm (GA) coupled to a finite-difference beam propagation method (FD-BPM) algorithm with paraxial approximation. These concepts and tools are used in this letter to design compact wavelength selective photodiodes.

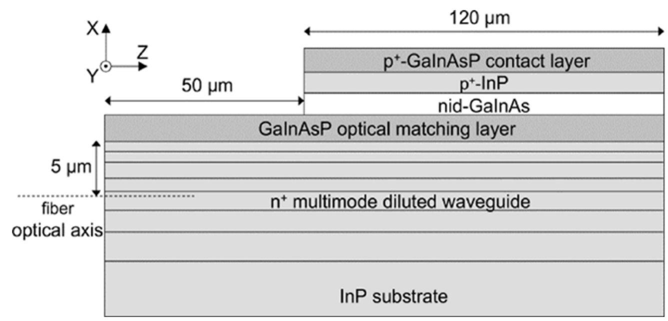


Fig. 1. Schematic structure of the photodiode, combining a multimode diluted input waveguide and an absorbing superstructure.

## II. Design and Optimization

The schematic structure of the photodiode is presented in Fig. 1. The input waveguide is a MDW, and consists in alternating InP layers, and thin $Ga_xIn_{1-x}As_{1-y}P_y$ quaternary layers. The $Ga_xIn_{1-x}As_{1-y}P_y$ bandgap wavelength is $\lambda_g = 1.18$ $\mu$m (denoted by $Q_{1.18}$ in this letter). A thicker $Q_{1.18}$ layer sits on top of the MDW, and acts as an optical matching layer [5]. The superstructure is made of a $Ga_{0.47}In_{0.53}$ As absorbing layer, a 1.8-$\mu$m-thick InP layer and a 0.2-$\mu$m-thick $Ga_xIn_{1-x}As_{1-y}P_y$ contact layer. The refractive indexes used in the FD-BPM are the same as in [5]. The planar input waveguide is 50 $\mu$m long and the superstructure is 20 $\mu$m wide and 120 $\mu$m long. Such dimensions allow high quantum efficiency and 10-Gb/s operation. The optical beam is injected into the MDW using a lensed fiber, centered 5 $\mu$m below the optical

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TABLE I
ELEVEN DIMENSIONAL SEARCH SPACE OF THE GENETIC ALGORITHM

| Thickness | Diluted $Q_{1.18}$ layers | Eight InP layers | Optical matching layer | GaInAs layer |
|---|---|---|---|---|
| **Min.** | 0.02 µm | 0 µm | 0 µm | 0 µm |
| **Max.** | 0.20 µm | 2 µm | 2 µm | 0.3 µm |

matching layer. That beam has a 5.8-$\mu$m mode field diameter (defined at $1/e$) at $\lambda = 1.55$ $\mu$m, and 5 $\mu$m at $\lambda = 1.3$ $\mu$m. The input facet is supposed perfectly antireflection-coated (both wavelengths and both polarizations).

The basic idea is to optimize the MDW structure in order to deviate a 1.55-$\mu$m beam toward the absorbing superstructure, while keeping straight propagation for its 1.3-$\mu$m counterpart. This can be done thanks to the multimode property of the waveguide, and to the material refractive index differences at both wavelengths. The first step in this optimization process is to define the search space of the GA (see Table I), i.e., to define what parameters can vary, within which limits. The eight thin $Q_{1.18}$ layers have an equal variable thickness, while the eight corresponding InP layers each have an independent variable thickness. The optical matching layer thickness can be up to 2 $\mu$m. The GaInAs thickness is limited to 0.3 $\mu$m in order to minimize evanescent absorption of the 1.3-$\mu$m wavelength. The resulting number of parameters is 11. The second step is to define a suitable fitness function, i.e., a number, evaluated for each structure, which the optimization process of the photodiode structure will tend to improve. The objectives are to obtain a high quantum efficiency at 1.55 $\mu$m, in both TE and TM modes (denoted $\eta_{1.55\mathrm{TE}}$ and $\eta_{1.55\mathrm{TM}}$) and a quantum efficiency as low as possible at 1.3 $\mu$m, also for both TE and TM modes (denoted $\eta_{1.3\mathrm{TE}}$ and $\eta_{1.3\mathrm{TM}}$). The four quantum efficiencies are computed by FD-BPM, for each structure. Extreme caution is required during the calculation of $\eta_{1.3\mathrm{TE}}$ and $\eta_{1.3\mathrm{TM}}$, because their target value is very low. Several fitness functions combining these objectives were tested, and the following proved to be suitable:

$$f = \mathrm{Log}\left(\frac{(\eta_{1.55\mathrm{TE}} + \eta_{1.55\mathrm{TM}})^2}{(\eta_{1.3\mathrm{TE}} + \eta_{1.3\mathrm{TM}} + 0.01)}\right). \quad (1)$$

In the above expression, the square puts weight on the 1.55-$\mu$m quantum efficiency. Adding 0.01 avoids obtaining uninteresting devices, for example with a 0.000 01% quantum efficiency at 1.3 $\mu$m and only 20% at 1.55 $\mu$m. This of course also limits the wavelength crosstalk target to about $-20$ dB. The logarithm is only to restrain the fitness function range in order to ease reading.

After these preparatory steps, the GA is launched, first coupled to a two-dimensional (2-D) FD-BPM, in order to optimize the structure with a limited computing time. The best one is then further optimized by using the first generation of GA coupled to a three-dimensional (3-D) FD-BPM. Such a two-step procedure is necessary to keep a reasonable computing time.

## III. Results and Analysis

The best device obtained from this optimization process has the following characteristics: the eight $Q_{1.18}$ layers in the diluted waveguide are 0.09 $\mu$m thick. Starting from the InP substrate, the thicknesses of the eight intermediate InP layers are: 1.34, 0.51, 1.20, 0.10, 1.11, 0.02, 0.05, 0.60 $\mu$m. The optical matching layer is 1.44 $\mu$m thick. The absorbing layer is only 0.16 $\mu$m thick.

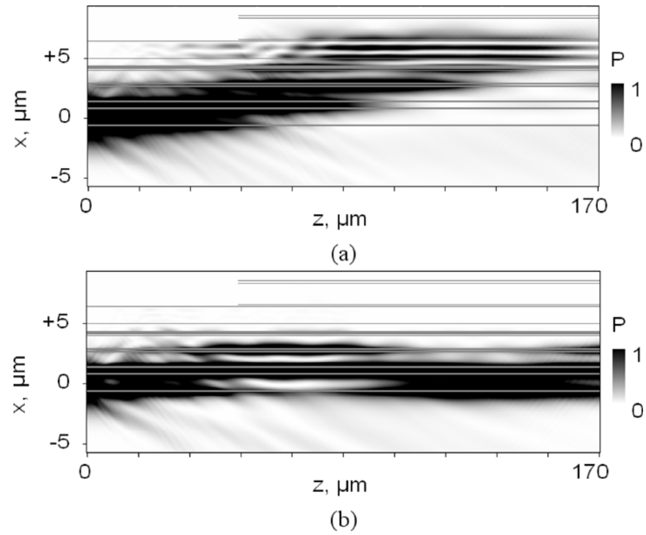


Fig. 2. (a) Simulated propagation of light at 1.55 $\mu$m and (b) 1.3 $\mu$m (2-D FD-BPM). Gray lines represent interfaces.

The quantum efficiencies, computed by 3-D FD-BPM, are $\eta_{1.55\mathrm{TE}} = 78\%$, $\eta_{1.55\mathrm{TM}} = 82\%$, $\eta_{1.3\mathrm{TE}} = 0.66\%$, and $\eta_{1.3\mathrm{TM}} = 0.66\%$, including coupling losses. The resulting crosstalk is $-20.7$ dB in TE mode and $-20.9$ dB in TM mode. The polarization dependence at 1.55 $\mu$m is as low as 0.22 dB. Fig. 2(a) and (b) shows the light propagation in the device, respectively, at 1.55 and 1.3 $\mu$m, in TM modes. At 1.55 $\mu$m, the MDW is bending the optical beam toward the absorbing superstructure, the same way as in [5]. At 1.3 $\mu$m, light propagates along the bottom of the MDW, therefore, no absorption takes place at this wavelength.

The wavelength sensitivity of the structure is estimated by approximating the refractive indexes using a linear dependence on wavelength (cf. materials references in [5]). The fiber mode size is also supposed to depend linearly on wavelength, in accordance with measurements we made. Fig. 3 presents the quantum efficiency variation versus wavelength, computed with 3-D FD-BPM. The device clearly filters wavelengths around 1.3 $\mu$m.

Due to the 20-$\mu$m width of the superstructure, the fiber $-1$-dB horizontal misalignment tolerance at 1.55 $\mu$m is 15 $\mu$m. Fig. 4 shows the effect on quantum efficiency, and on wavelength crosstalk, of the fiber vertical misalignment. The high tolerance at 1.55 $\mu$m is typical of such structures. But at 1.3 $\mu$m, the behavior of the MDW appears strongly dependant on the vertical position of the fiber. An injection close to the substrate results in a very low quantum efficiency, and therefore, in a low wavelength crosstalk (see inset in Fig. 4). An injection near the MDW surface results in a drastic increase of the 1.3-$\mu$m quantum efficiency, and therefore, in a rapid degradation of the wavelength crosstalk. A modal analysis of this behavior is difficult because numerous modes propagate in the MDW (five to seven depending on wavelength and optical polarization).

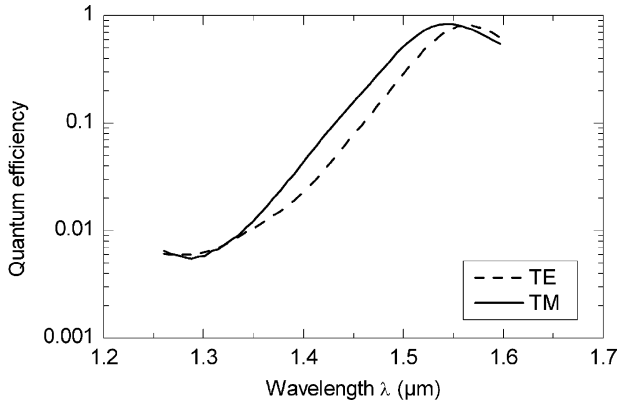


Fig. 3. Quantum efficiency variations in TE and TM modes versus wavelength for the best structure (3-D FD-BPM results).

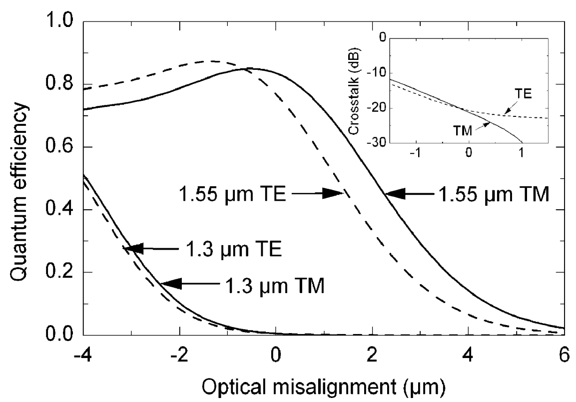


Fig. 4. Quantum efficiency variations versus lensed fiber vertical misalignment (3-D FD-BPM results). The substrate is toward positive values. The inset shows the wavelength crosstalk versus misalignment.

However, we believe that the differences between 1.3- and 1.55-$\mu$m behaviors can be partially understood considering overlap integrals between all modes. At 1.55 $\mu$m, the modes are very wide and each one overlaps strongly with at least another one. This results in a pseudoperiodic up and down movement of light in the waveguide, as shown in [5]. At 1.3 $\mu$m, propagating modes are narrower and overlap poorly. Therefore, the bottom part of the MDW can be considered somehow isolated from the upper part, at the scale of the photodiode length.

The cutoff frequency can be estimated from [7]. For a given photodiode surface, there is an optimum undoped layer thickness to achieve high bandwidth. If only the absorbing layer is undoped, the cutoff frequency is only 4 GHz, due to high capacitance. But a 11.5-GHz cutoff frequency is obtained if the 1.44-$\mu$m optical matching layer is also undoped. In this case, [8] is used for the bandwidth calculation since absorption takes place only in the upper 0.16-$\mu$m GaInAs layer. Such a photodiode is suitable for high-performance and low-cost modules, up to 10 Gb/s, achieving 0.96 A/W at 1.55 $\mu$m and $-20.7$-dB crosstalk.

The fabrication process would be the same as in [5], but would require a higher accuracy on thicknesses and compositions. In order to keep the crosstalk under $-20$ dB in TE and TM modes, the thicknesses of MDW InP layers should have a $\pm 4\%$ accuracy, the thin $Q_{1.18}$ layers thicknesses should be comprised between 0.085 and 0.11 $\mu$m. The thickness of the optical matching layer is the most critical and should be comprised between 1.39 and 1.45 $\mu$m.

## IV. Conclusion

An original high-performance and very compact waveguide p-i-n photodiode structure has been proposed, to achieve high 1.55-$\mu$m responsivity, and low 1.3/1.55-$\mu$m crosstalk. It is based on an evanescent photodiode structure including a carefully optimized MDW, which lets the 1.3-$\mu$m wavelength propagate through the device while bending the 1.55-$\mu$m wavelength toward the absorbing layer. A 3-D FD-BPM simulation shows that this device can achieve 0.96 A/W at 1.55 $\mu$m, including coupling losses, with 1.3/1.55-$\mu$m crosstalk as low as $-20$ dB. The proposed device is designed for hybridization on silicon platform for low-cost 10-Gb/s modules.

## References

[1] K. Kato, M. Yuda, A. Kozen, Y. Muramoto, K. Noguchi, and O. Nakajima, "Selective-area impurity-doped planar edge-coupled waveguide photodiode (SIMPLE-WGPD) for low-cost, low-power-consumption optical hybrid modules," *Electron. Lett.*, vol. 32, no. 22, pp. 2078–2079, Oct. 1996.

[2] Y. Kuhara, Y. Fujimura, H. Nakanishi, Y. Iguchi, H. Terauchi, and N. Yamabayashi, "A coaxial-type 1.3-1.5 $\mu$m WDM-PD module for optical access networks," *J. Lightw. Technol.*, vol. 14, no. 10, pp. 2374–2381, Oct. 1996.

[3] A. Salvador, B. Sverdlov, T. Lehner, A. Botchkarev, F. Huang, and H. Morkoç, "Resonant cavity enhanced InP/InGaAs photodiode on Si using epitaxial liftoff," *Appl. Phys. Lett.*, vol. 65, no. 15, pp. 1880–1882, Oct. 1994.

[4] Y. Suzuki, R. Iga, T. Yamada, H. Sugiura, and M. Naganuma, "Crosstalk characteristics of a 1.3-$\mu$m/1.5-$\mu$m wavelength demultiplexing photodetector using laser-assisted MOMBE growth," *J. Lightw. Technol.*, vol. 17, no. 3, pp. 483–489, Mar. 1999.

[5] V. Magnin, L. Giraudet, J. Harari, J. Decobert, P. Pagnot, E. Boucherez, and D. Decoster, "Design, optimization and fabrication of side-illuminated p-i-n photodetectors with high responsivity and high alignment tolerance for 1.3 $\mu$m and 1.55 $\mu$m wavelength use," *J. Lightw. Technol.*, vol. 20, no. 3, pp. 477–488, Mar. 2002.

[6] V. Magnin, J. Harari, and D. Decoster, "Numerical study of polarization selective side-illuminated pin photodetectors grown on InP substrate for hybridization on silicon platform," *IEE Optoelectron.*, vol. 151, no. 3, pp. 171–176, Jun. 2004.

[7] K. Kato, "Ultrawide-band/high-frequency photodetectors," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 7, pp. 1265–1281, Jul. 1999.

[8] R. B. Emmons, "Avalanche photodiode frequency response," *J. Appl. Phys.*, vol. 38, pp. 3705–3714, Aug. 1967.