

# Novel Group Delay Lines Formed by Multi Quantum Well Defective Photonic Crystals

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In this paper, highly efficient novel group delay lines in guided-wave multi-quantum-well one-dimensional photonic bandgap structures are designed for very high rate data streams in all-optical signal processors and telecommunications systems by using the Floquet-Bloch formalism.

**Keywords:** guided-wave optics, photonic bandgap structures, multi quantum wells

## Introduction

Optical delay lines can be used in a large number of optical signal processing applications including data storage, parallel-serial converters, optically-controlled phased array antennas and optical communications. Compact delay devices to be used with ultrashort pulses are also required by demultiplexing and optical computing systems. Photonic bandgap (PBG) crystals are one of the most suitable materials for fabricating very compact and fully integrable optical delay lines. Wideband ( $> 5$  GHz) transmit/receive phased array antennas require low-cost and low-loss delay lines. At the best, tens of millimeters long lines can be fabricated by electronic technology to obtain hundreds of picosecond delays [1]. GaAs-based PBG structures can be used to produce low-cost, low-loss either fixed or programmable delay lines. 1D PBG delay lines (4.5  $\mu\text{m}$  long, 200 fs at  $\lambda = 1.038 \mu\text{m}$ ) have been experimentally studied in GaAs/AlAs multistack architectures [2] for use in optical beam steering for phased array antennas. In Ref. [3] photonic crystal waveguide in Si has been used to obtain optical delay lines, 20  $\mu\text{m}$  long, with delay of the order of 600 fs with pulses 110 fs wide, for optical signal processing applications.

In the optical communication systems delay lines are fundamental elements in tunable optical add/drop multiplexing (OADM), compensation of polarization mode dispersion (PMD), suppression of cross-phase modulation (XPM) and packet timing in optical time division multiplexing (OTDM). A tunable OADM using fiber optic tapped delay line (OTDL) transversal filter has been proposed [4] with a round-trip delay of 2 ps. The effects of the PMD are the signal degradation and data loss which results in a power penalty and outage probability. Following criteria proposed by ITU (International Telecommunication Union), the maximum tolerable differential group delay (PGD) is 10% of the bit duration to maintain acceptable receiver error rates. For 10 Gb/s and 40 Gb/s systems, a PMD of 10 ps and 2.5 ps, respectively, is recommended. Typical PMD compensators consist of a polarization controller followed by a fixed or variable DGD section.

XPM is another strong critical effect in long-distance WDM transmissions, which limits the maximum power that can be injected in the transmission line. Optical delay lines are the basic elements of the XPM suppressors. A total delay of 80 ps has been proved useful to strongly reduce the penalties in a 10x10 Gb/s transmission over five spans of 100 km [5]. Fast wavelength switching has been demonstrated [6] using an OTDM channel selector based on both parallel and serial optical delay line. Wavelength switching was achieved with an average latency of 100 ps for a parallel delay structure on 16 channels at 40 Gb/s and an aggregate bit rate of 160 Gb/s.

In this paper the design of novel guided-wave MQW 1D defective PBG delay lines is described. The new configuration can be used to produce delay elements for applications both in optical signal processing and telecommunication systems. Tunability is also allowed by varying the refractive index of the materials with the use of an external electric field.

## Delay line architecture

The schematic diagram of the delay line including periodicity defects is shown in Fig. 1.

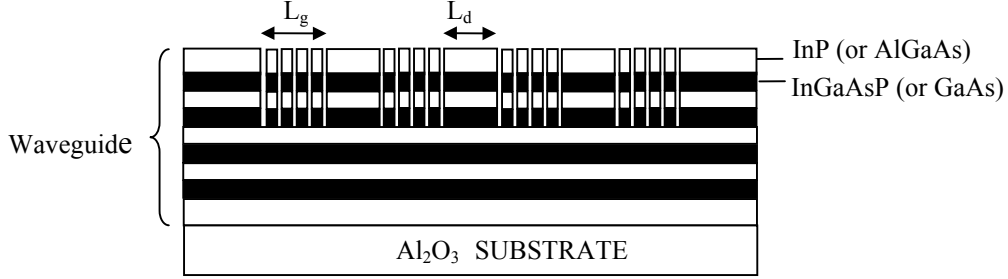


Fig. 1. Scheme of guided-wave planar MQW single grating.

The periodic perturbation, having rectangular profile with tooth width  $w$ , period  $\Lambda$  and length  $L_g$ , is partially etched inside a MQW with four wells and five barriers, each layer being isotropic and homogeneous. The configuration in Fig. 1 has been demonstrated to be highly efficient with respect to the photonic bandgap effect [7]. A number of  $N+1$  gratings, each one having  $M$  periods, are separated by  $N$  unperturbed waveguide sections (defects), each one  $L_d$  long. Two types of MQW structures have been investigated: one based on GaAs technology to design delay lines at wavelengths around 850 nm; the other, based on InP, is focused for applications at 1550 nm. An  $\text{Al}_2\text{O}_3$  substrate has been considered. In both cases, the grating depth is 80 nm (50% etched) and the duty cycle 70%. The grating period is 157 nm for GaAs and 357 nm for InP. Index contrast is 2.49 for the GaAs structure and 2.31 for the InP one.

According to the Floquet-Bloch formalism [7-8], the electromagnetic field inside the grating region has been described as a combination of two rigorous solutions (forward and backward leaky modes) of the lossy infinite structure without any approximation for guided-wave high contrast gratings, both partially or fully etched. Then, these solutions have been used in a closed-form multiple reflection cavity model, to take into account the presence of an arbitrary numbers of defects. The group delay time  $\delta$ , suffered by the optical wave traveling along the MQW structure, has been calculated with respect to vacuum as:

$$\delta = \frac{L}{v_g} - \frac{L}{c} = \frac{d\varphi}{d\omega} + L \left( \frac{d\beta_u}{d\omega} - \frac{1}{c} \right) \quad (1)$$

where  $v_g$  and  $c$  are the group velocities inside the grating and in vacuum, respectively,  $\varphi$  is the transmission phase,  $\beta_u$  is the unperturbed waveguide propagation constant and  $L$  is the delay line length. To characterize the behaviour of any delay line and compare the performance, an appropriate dimensionless figure-of-merit has been used, i.e. the group index  $n_g = \delta c / L + 1$ .

## Numerical results

TE optical polarization has been considered. A number of calculations have been carried out by varying the device parameters, i.e.  $N$ ,  $M$ ,  $L_d$ ,  $L_g$ . The aim was to maximize the value of  $n_g$ , i.e. to obtain the maximum delay with minimum total length. Another parameter has been simultaneously considered, the time duration of the incident signal pulse, which is very important when very fast ultrashort data streams are considered in telecommunications systems. In Fig. 2 the spectral behaviour of transmittivity and group delay in case of  $M = 4$  periods for both GaAs- and InP-based MQW structures are sketched.

A number of cases have been considered by changing  $N$ . All the gratings and defects of the structures are equal. As we can see from the curves, the transmittivity and delay bandwidth become more and more flat as large as the number of defects, so giving the possibility to transmit narrower delayed pulses. However, the delay line length increases with  $N$  and, then, the best trade-off between conflicting requirements must be found.

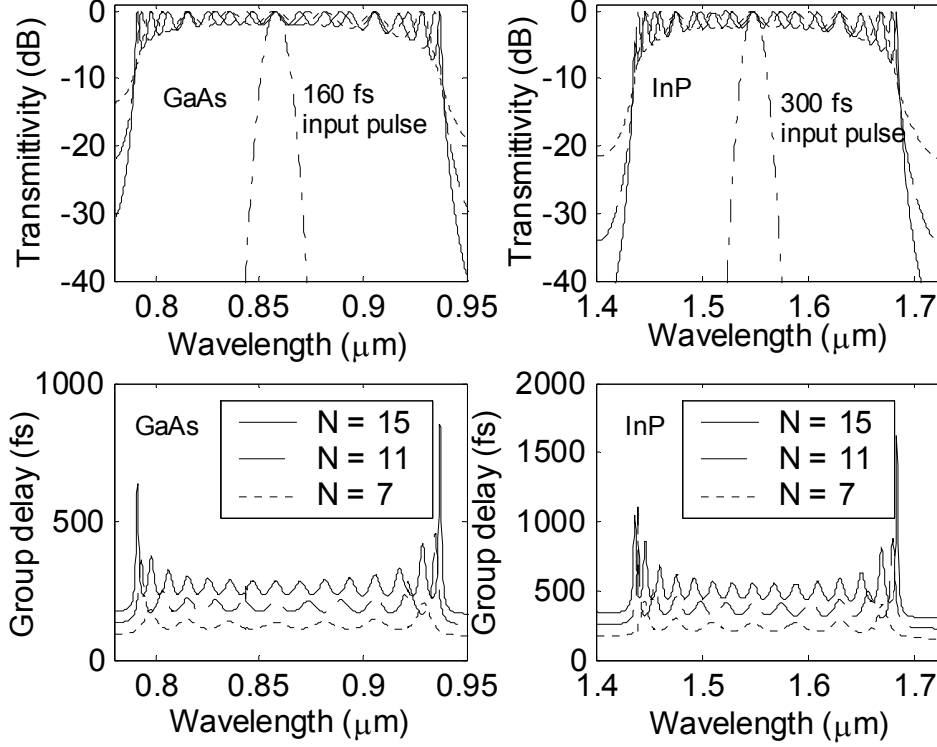


Fig. 2. Transmittivity and delay for GaAs- and InP-based defective PBG delay lines.

Therefore, the different cases have been compared in terms of figure-of-merit  $n_g = \delta c / L + 1$ , showing that the optimal number of defects is  $N = 15$  in both technologies. Table I summarizes the performance parameters of the best delay lines investigated.

Table I. Delay line performance.

Parameters	GaAs structure	InP structure
Grating length, $L_g$ (nm)	628 (M = 4)	1428 (M = 4)
Defect length, $L_d$ (nm)	538	1224
Number of defects, $N$	15 (optimal)	15 (optimal)
Delay line length (nm)	18126	41215
Group index, $n_g$	5.3	4.62
Wavelength, $\lambda$ (nm)	858	1548
Delay, $\delta$ (fs)	260	498
Pulse time duration (fs)	160	300
Data stream rate (Tb/s)	2.5	1.33

Other calculations made with  $N = 150$  for InP structure ( $L \sim 400 \mu\text{m}$ ) have given delays as large as 4.9 ps with a bit rate of 40 Gb/s. It is important, in the choice of the structure parameters, to find the resonance condition inside the passive cavities formed by two neighbour gratings, in order to

form an allowed band inside the bandgap spectral region of the single grating. It critically depends on the ratio between the defect length and the grating tooth width. This condition has been found in our structures as  $L_d/w = 4.9$ . The bandwidth enlargement and its relevant ripple, which we can note from Fig. 2, is due to the presence of defects and is also related to the small length of the gratings, having only four periods in these cases. In fact, with increasing M, the device spectral behaviour tends to approach that of a single, very long grating, the influence of the defects tends to disappear, the bandwidth dramatically decreases and the delay increases. Then, this behaviour could be followed by delay lines with large delays and very narrow bandwidths, in applications where a single monochromatic CW signal (not pulsed) must be transmitted [9].

The high performance of these delay lines is demonstrated by the value of group index, larger than 4.5 in both cases. This means that the MQW PBG structure delays the input pulse more than in a homogeneous material characterized by the maximum refractive index of the structure, i.e. 3.6 for the first and 3.45 for the second structure. Moreover, it is clear from Table I that ultrafast data streams ( $>1$  Tb/s) can be delayed and transmitted by these devices.

We have compared the  $n_g$  values with those typical,  $\sim 4$  (i.e. 250 ps after 25 mm) of the GaAs-based OTDLs for beam forming, and proved another advantage of our architecture. Moreover, the total loss in our configurations is 2 dB, well lower than the OTDL typical values,  $> 10$  dB.

In conclusion, we have presented the design of a new configuration of optical delay lines. The novel delay elements are formed by a guided-wave MQW structure including periodicity defects. This new configuration is fully versatile since it can be adopted to produce optical delay lines for both optical signal processing and telecommunications systems. In fact, it is possible to vary the geometrical and physical parameters to obtain the desired value of the group delay. Tunability can also be accomplished in these devices by decreasing the semiconductor layer indices by the injection of electrons, or by using nonlinear effects induced by high input powers, or by applying electric fields [10]. This performance, together with the full monolithic integration allowed by waveguiding MQW PBG structures, well demonstrate the theoretical superiority of these MQW PBG architectures as group delay lines.

- [1] Santec Corp. 2002 Products, <http://www.santec.com>.
- [2] M. Scalora, R. J. Flinn, S. B. Reinhardt, R.L. Fork, M.J. Bloemer, M.D. Tocci, C.M. Bowden, H. S. Ledbetter, J.M. Bendickson, J.P. Dowling and R.P. Leavitt, *Phys. Review E* **54**, R1078-R1081, 1996.
- [3] Y. Sugimoto, S. Lan, S. Nishikawa, N. Ikeda, H. Ishikawa and K. Asakawa, *Appl. Phys. Lett.* **81**, 1946-1948, 2002.
- [4] C.-H. Yoon, H. Kim and J.-D. Shin, *IEEE CLEO Conf. Proc.*, pp. 785-786, 1999.
- [5] G. Bellotti, S. Bigo, P.-Y. Cortes, S. Gauchard and S. La Rochelle, *IEEE Photon. Tech. Lett.* **12**, 1403-1405, 2000.
- [6] B. C. Wang, I. Glesk, R. J. Runser and P. R. Prucnal, *Optics Express* **8**, 599-604, 2001.
- [7] V. M. N. Passaro, F. De Leonardis, C. Ciminelli and M. N. Armenise, submitted to *J. Opt. A: Pure and Appl. Opt.*
- [8] A. Giorgio, A. G. Perri and M. N. Armenise, *J. Lightwave Technol.* **19**, 1598-1613, 2001.
- [9] L.J. Gamble, W. M. Diffey, S. T. Cole, R. L. Fork, D. K. Jones, T. R. Nelson, Jr., J. P. Loehr and J. E. Ehret, *Optics Express* **5**, 267-272, 1999.
- [10] T. R. Nelson, Jr., J. P. Loehr, Q. Xie, J. E. Ehret, J. E. Van Nostrand, L. Gamble, D. K. Jones, S. T. Cole, R. A. Trimm, W. M. Diffey, R. L. Fork and A. S. Keys, *Proc. SPIE* **3714**, 12-23, 1999.