

Photonic Integrated Circuit for Wavelength Division Multiplexing

FIELD OF INVENTION

5 The present document relates to a photonic integrated circuit (PIC) for multiplexing optical signals in a wavelength division multiplexing (WDM) system. In particular, the document relates to a method and system for reducing the size of a PIC for multiplexing optical signals in a WDM system.

10 BACKGROUND

PICs have been developed to reduce packaging costs and the footprint of multi-wavelength emitters. One main market is the metropolitan area network.

15 PICs are now foreseen for the access network. In the next generation of access networks, wavelength division multiplexing (WDM) will emerge to increase the flexibility of access networks, the number of subscribers and the optical budget (power splitters might be replaced by wavelength demultiplexers, which will also increase the number of possible
20 subscribers).

In fiber-optic communications, WDM is a technology which multiplexes multiple optical carrier signals on a single optical waveguide (e.g. an optical fiber) by using different wavelengths to carry different signals. This
25 allows for a multiplication in capacity, in addition to enabling bidirectional communication over the same optical waveguide. In a WDM system, a multiplexer is used to merge the different optical signals corresponding to different wavelengths together onto the same waveguide, and a demultiplexer is typically used to isolate the different optical signals from
30 the waveguide. When a device does both simultaneously, it can be used as an optical add-drop multiplexer.

SUMMARY

In access networks, the cost of network components, e.g. the WDM transmitters, is an important issue. As a result, WDM will most likely be
5 coarse (e.g. with a 20 nm wavelength spacing) in order to use uncooled optical emitters. Furthermore, in order to provide a WDM transmitter at low manufacturing cost, it is desirable to achieve a high degree of integration, i.e. it is desirable to provide a WDM transmitter which can transmit light at a high number of different wavelengths on the limited
10 space of a PIC. The present document describes such a WDM transmitter and a corresponding method for implementing such a WDM transmitter.

According to an aspect an optical transmitter or optical emitter is described. In particular, an optical CWDM emitter or transmitter is
15 described. The emitter or transmitter may be integrated on a photonic integrated circuit (PIC). The transmitter may be configured to generate a plurality of optical signals at a corresponding plurality of different wavelengths multiplexed onto an output waveguide. The wavelengths may be in the 1300 nm to 1600 nm range. The spacing between the wavelengths
20 may be about 20 nm or more.

The transmitter may comprise a first and a second converter comprising different first and second active materials configured to emit light at a first and a different second wavelength. The first and second converters may be
25 electro-optical converters configured to convert an electrical signal into an optical signal. In particular, the converter may be configured to convert a modulated electrical signal into a modulated optical signal.

The transmitter may comprise a first converter waveguide traversing or
30 passing through the first and second material of the first and second converter. The second material may be at an output end of the first

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converter waveguide and the first material may be at an input end (e.g. a rear end of the transmitter), upstream or opposite of the output end, of the first converter waveguide. The output end of the first converter waveguide may be directed towards the output end of the optical transmitter, i.e. towards the output waveguide. In other words, the output end of the first converter waveguide typically leads to the output waveguide.

The second active material may be transparent to the light at the first wavelength. On the other hand, the first active material may be configured to absorb the light at the second wavelength. This may be achieved by selecting appropriate semiconducting materials, e.g. appropriate compositions of Indium (In), Gallium (Ga), Aluminium (Al), Arsenide (As) and/or Phosphorous (P). In particular, this may be achieved if the second wavelength is smaller than the first wavelength.

The converters may be separated by a semitransparent reflector positioned at an output end of the first converter and at an input end of the second converter, the semitransparent reflector being substantially reflective to light at the second wavelength. By doing this, rearward crosstalk between the first and second wavelengths can be reduced. In addition, the semitransparent reflector may be transparent to light at the first wavelength.

The first converter may comprise a first laser using the first active material and the second converter may comprise a second laser using the second active material. The lasers may be distributed feedback lasers (DFB). Such lasers may comprise a grating along the first converter waveguide. Such a grating may comprise a periodic variation of the refractive index of the material of the first converter waveguide, wherein the length of a periodic variation is typically referred to as a grating period or grating pitch Λ . In

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particular, the first converter may comprise a first grating at a first grating period, wherein the first grating period is selected based on to the first wavelength, i.e. the first grating period is associated with the first wavelength. In addition, the second converter may comprise a second grating at a second grating period, wherein the second grating period is selected based to the second wavelength, i.e. the second grating period is associated with the second wavelength. The first and second gratings, i.e. their effective refractive indexes n_{eff} and/or their grating periods, are typically configured to have a high reflectivity at the first and second wavelength, respectively. Furthermore, the first and second grating may be configured to be transparent at wavelengths other than the first and second wavelength, respectively.

The transmitter may comprise K groups of N converters C_{kn} , $k=1, \dots, K$ and $n=1, \dots, N$ with $K>1$ and $N>1$. That is to say, in addition to the first and second converter which may be part of a first group of converters, the transmitter may comprise additional groups of converters. K may be greater or equal to 2, 4 and/or 8. K may be smaller or equal to 4, 8, 16 or 32. N may be greater or equal to 2, 3, 4, 8. N may be smaller or equal to 4, 8, 16 or 32. Each group of converters may be configured to generate N optical signals S_{kn} at wavelengths λ_{kn} , multiplexed onto a corresponding converter waveguide W_k . As a result a serially multiplexed optical signal S_k comprising N different wavelengths λ_{kn} , $n=1, \dots, N$, may be obtained at the output end of the converter waveguide W_k . That is to say, in addition to the first converter waveguide the transmitter may comprise further converter waveguides W_k for the other additional groups of converters. The converters C_{kn} may comprise different active materials M_{kn} configured to emit light at the wavelength λ_{kn} , respectively. That is to say, each converter may comprise a different active material configured to emit light at a different wavelength.

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As already indicated above, the first and second converter may correspond to the converters C_{11} and C_{12} , respectively. Furthermore, the first and second active materials may correspond to the materials M_{11} and M_{12} , respectively. In addition, the first converter waveguide may correspond to the converter waveguide W_1 traversing the first group of N optical converters C_{1n} , $n=1, \dots, N$.

In a similar manner to the first converter waveguide, the converter waveguides W_k , $k=1, \dots, K$, traverse the N active materials M_{kn} , $n=1, \dots, N$ of the k^{th} group of optical converters. In other words, each group of optical converters is traversed by a dedicated converter waveguide W_k . Without loss of generality, the indexing of the converters, wavelengths and materials is such that (for all k) material M_{kN} is at an output end of the waveguide W_k and material M_{k1} is at an input end, upstream and/or opposite of the output end, of the waveguide W_k .

In order to perform the serial multiplexing along the k^{th} group of converters, the material M_{ki} may be configured to be transparent to and/or to leave unaffected light at a wavelength λ_{kj} with $j < i$. This condition may be met for all $i, j=1, \dots, N$. Alternatively or in addition, material M_{ki} may be configured to absorb light at a wavelength λ_{kj} with $j > i$. This condition may be met for all $i, j=1, \dots, N$. In other words, the different materials M_{ki} may cause a selective absorption or passage of light, depending on the wavelength λ_{kj} of the light. Light at a wavelength λ_{kj} with $j < i$ may pass the material M_{ki} , while light at a wavelength λ_{kj} with $j > i$ may be absorbed by material M_{ki} .

The transmitter may comprise an optical combiner configured to multiplex the K serially multiplexed optical signals S_k at the output end of the K converter waveguides W_k onto the output waveguide. This may be done

using parallel multiplexing techniques, such as AWG (Arrayed Waveguide Grating) multiplexing or MMI (Multi-Mode Interference) multiplexing.

The K groups of converters C_{kn} may be laterally spaced with respect to one another such that the output end of the K combiner waveguides W_k are at a lateral distance with respect to one another. In other words, the groups of converters may be placed in parallel with respect to their respective combiner waveguides W_k . I.e. the combiner waveguides W_k traversing the K groups of converters C_{kn} may be parallel. The combiner may comprise a first merging section, where the lateral distance between the K combiner waveguides W_k is progressively reduced. Furthermore, the combiner may comprise a second merging section, where the light at different wavelengths λ_{kn} carried in the combiner waveguides W_k , i.e. where the K serially multiplexed optical signals S_k , are superimposed within a joint waveguide leading to the output waveguide. The first merging section may comprise a plurality of S-bend waveguides configured to progressively reduce the distance between the K combiner waveguides W_k . Preferably, each combiner waveguide W_k is coupled to a corresponding S-bend waveguide.

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In order to reduce the crosstalk between wavelengths which are multiplexed onto a joint combiner waveguide W_k , the active materials M_{kn} and the corresponding wavelengths λ_{kn} may be arranged such that for some or all pairs of neighboring converters C_{ki} , C_{ki+1} of the k^{th} group of converters along the combiner waveguide W_k , there are K-1 wavelengths of the set of multiplexed wavelengths λ_{kn} , $k=1, \dots, K$ and $n=1, \dots, N$, which are greater than wavelength λ_{ki+1} emitted by converter C_{ki+1} and smaller than wavelength λ_{ki} emitted by converter C_{ki} . In an embodiment, the active materials M_{kn} and the corresponding wavelengths λ_{kn} may be arranged such that $\lambda_{kn} > \lambda_{in}$, for any $k > i$, and $\lambda_{kn} > \lambda_{ki}$, for any $i > n$.

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As outlined above, the converters C_{kn} , $k=1,\dots,K$ and $n=1,\dots,N$ may be lasers, in particular DFB lasers. As such, the converters C_{kn} may comprise corresponding gratings G_{kn} , $k=1,\dots,K$ and $n=1,\dots,N$ at grating periods Λ_{kn} , $k=1,\dots,K$ and $n=1,\dots,N$, respectively. The gratings G_{kn} may be implemented as periodic variations of the refractive index of the converter waveguide W_k within the converter C_{kn} . That is to say, the grating G_{kn} may be implemented within the converter waveguide W_k , and the grating may be different for each converter traversed by the converter waveguide. Alternatively or in addition, the gratings G_{kn} may be implemented in a separate layer parallel to the converter waveguide W_k . A grating period Λ_{kn} of the grating G_{kn} may be selected such that light at the wavelength λ_{kn} is reflected, i.e. the grating period Λ_{kn} of the grating G_{kn} may be associated with the wavelength λ_{kn} . Furthermore, the grating period Λ_{kn} of the grating G_{kn} may be selected such that it is transparent to light at other wavelengths than wavelength λ_{kn} . In particular, the grating period Λ_{kn} of the grating G_{kn} may be selected such that it is transparent to light at wavelength λ_{jn} , for $j < k$. In an embodiment, the grating period Λ_{kn} is selected as

$$\Lambda_{kn} = \frac{1}{2n_{eff}} \lambda_{kn},$$

wherein n_{eff} is the effective index of the grating G_{kn} . That is to say, the grating period of a converter may be selected to be proportional to the wavelength emitted by the converter.

According to a further aspect, a method for generating a plurality of optical signals at a corresponding plurality of different wavelengths multiplexed onto an output waveguide is described. The method may comprise the step of providing a first and second converter comprising different first and second active materials configured to emit light at a first and a different second wavelength. In addition, the method may comprise the step of providing a first converter waveguide traversing the first and

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second material of the first and second converter, the second material being at an output end of the first converter waveguide and the first material being at an input end, upstream of the output end, of the first converter waveguide. The second active material may be transparent to the light at the first wavelength. The output end of the first converter waveguide may lead to the output waveguide.

According to another aspect an optical network, e.g. an optical access network, comprising the optical transmitter or optical emitter described in the present document is described. The optical network may further comprise an optical transmission medium for transmitting the multiplexed optical signal. Furthermore, the optical network may comprise a corresponding optical receiver.

SHORT DESCRIPTION OF THE FIGURES

Some embodiments of apparatus and methods in accordance with embodiments of the present invention are now described, by way of example only, and with reference to the accompanying drawings, in which:

Figure 1 shows a schematic view of an example of an AWG multiplexer and a plurality of electro-optical converters;

Figures 2 and 2a show views of an example of a MMI multiplexer and a plurality of electro-optical converters;

Figure 3 shows a schematic view of an example of a MMI multiplexer and a plurality of groups of electro-optical converters using serial multiplexing;

Figure 4 shows a schematic view of an example of a group of electro-optical converters using serial multiplexing;

Figure 5 shows an example of a MMI multiplexer and a plurality of groups of electro-optical converters using serial multiplexing; and

Figure 6 shows a schematic view of another example of a MMI multiplexer and a plurality of groups of electro-optical converters using serial multiplexing.

5 DESCRIPTION OF PREFERRED EMBODIMENTS

Integrated CWDM emitters which generate light at a plurality of wavelengths (e.g. four wavelengths) may be based on different concepts. The concepts may differ on the way that the light generated by a plurality of CWDM light sources is multiplexed onto a joint optical waveguide.

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A first option of multiplexing the light at different wavelength may use an Arrayed Waveguide Grating (AWG) based on silicon on insulator (SOI). An AWG multiplexer is usually built as a PIC, where the light coming from a multitude of input fibers, i.e. a multitude of optical channels, enters a first waveguide section, then propagates through several waveguides of different length and enters a second waveguide section, and is finally coupled into an output fiber. Wavelength multiplexing is based on an interference effect and the different optical path lengths of the waveguides; at least some frequency components of the input fibers propagate through the waveguides, and the output in the output fiber results from the superposition (interference) of these contributions of the at least some frequency components.

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Figure 1 shows an exemplary schematic view of a PIC comprising a plurality of electro-optical converters 11 (e.g. four discrete CWDM lasers) and an AWG multiplexer. The AWG multiplexer may comprise a plurality of waveguides 12, a first multimode section 13, a plurality of arrayed waveguides 16, a second multimode section 16 and an output waveguide 14. The electro-optical converters 11 are configured to convert electronic signals to optical signals, e.g. pulses of light at a specific wavelength. Light from the electro-optical converters 11 propagates through the first

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plurality of waveguides 12 and enters the first multimode section 13. From the first multimode section 13, the light enters the arrayed waveguides 16. The arrayed waveguides 16 are of different length so that an interference pattern is produced at the second multimode section 16. The plurality of
5 waveguides 12, the first multimode section 13 and the plurality of arrayed waveguides 16 are arranged so that the produced interference pattern focuses the signals into the output waveguide 14 (e.g. a multimode waveguide).

10 The use of AWG based multiplexers may lead to low multiplexing losses. The AWG based multiplexers can be scaled for a higher number of channels, i.e. for a higher number of different CWDM wavelengths. However, this solution may be very costly as (i) the hybrid integration may require delicate alignment between passive and active waveguides and
15 components; and as (ii) the monolithic integration may lead to large PIC-chip dimensions.

Another option for multiplexing light of a plurality of CWDM lasers is an integrated MMI (multimode interference) device or multiplexer. A MMI
20 multiplexer may be built as a PIC, where the light coming from a plurality of input fibers propagates through a multimode waveguide section into an output waveguide (e.g. an optical fiber). The basis of MMI multiplexers is the self-imaging principle of MMI. That is to say, by selecting the width and length of the multimode waveguide section, self-images of the different
25 wavelengths can be coupled into the output waveguide.

Figures 2 and 2a show schematic exemplary views of an MMI multiplexer in combination with a plurality of electro-optical converters 21 (e.g. four CWDM lasers). The MMI multiplexer may comprise a plurality of waveguides
30 22, a multimode section 23 and an output waveguide 24. The electro-optical converters 21 are configured to convert electronic signals to optical

signals, e.g. pulses of light at specific wavelengths. The electro-optical converters 21 may be distributed feedback (DFB) lasers. The light from the electro-optical converters 21 propagates through the plurality of waveguides 22 and enters the multimode section 23. Typically, the plurality of waveguides 22 corresponds to a plurality of S-bend waveguides. Each mode in the multimode section 23 propagates with a different phase velocity and hence an interference pattern is produced that is dependent on the position along the multimode section 23. By selecting the width and length of the multimode section 23, and the configuration and position of the output waveguide 24 downstream of the multimode section 23, the different wavelengths provided by the plurality of electro-optical converters 21 can be multiplexed into the output waveguide 24.

Preferably, the electro-optical converters 21 are laterally positioned such that the curvature of each waveguide 22 does not exceed a predefined threshold in order to avoid signal losses. In other words, the curvature radius is preferably sufficiently large. In other words, the electro-optical converters 21 are laterally offset and the length of the S-bend waveguide 22 leading from a respective converter 21 to the multimode section 23 may be selected such that the losses due to the S-bends are kept below the predefined threshold.

The PIC comprising four CWDM lasers and an MMI multiplexer to generate four optical channels as depicted in Figs. 2 and 2a may require around 2 mm² per device. That is to say, up to 3500 devices comprising the CWDM lasers and the MMI multiplexer may be manufactured from a 4 inch wafer. The multiplexing losses of the MMI multiplexer are at around 6 dB, which can be compensated with a booster. However, for 8 CWDM channels, i.e. when doubling the number of channels, the size of the device will roughly have to be multiplied by 4 to maintain the same curvature radius of the S-bend waveguides 22. This will reduce the number of PICs which can be

manufactured from a 4 inch wafer to less than 1000, thus increasing the cost of the integrated CWDM transmitter. Moreover, the MMI multiplexer losses may be greater than 9 dB, and the passive waveguides of the MMI multiplexer may be much longer. As a consequence, the fabrication yield and the multiplexing losses might become prohibitive when increasing the number of laterally placed DFB lasers (i.e. converters 21).

The above mentioned multiplexing schemes which are based on AWG (Fig. 1) and on MMI (Figs. 2, 2a) will be referred to as parallel multiplexing, as the schemes are directed at multiplexing the light originating from a plurality of parallel (i.e. laterally spaced) electro-optical converters 11, 21. In order to allow for a higher integration of CWDM transmitters, i.e. in order to allow for a higher number of CWDM wavelengths to be generated and multiplexed on the limited space of a PIC, a so called serial multiplexing of wavelengths is described in the following which can be used alternatively or in addition to the parallel multiplexing.

Figure 3 shows a schematic view of an MMI multiplexer using both parallel multiplexing as outlined in the context of Figs. 2 and 2a and serial multiplexing. The converters 21 are replaced by groups of converters 31aa, 31ab and 31ba, 31bb placed in series along the signal path. Fig. 3 illustrates two branches or groups of two converters 31aa, 31ab and 31ba, 31bb which are configured to generate light at different wavelengths. As described with reference to Figure 2, an MMI multiplexer may be used to multiplex the light coming from the plurality of electro-optical converters 31aa, 31ab, 31ba, 31bb. The MMI multiplexer preferably comprises a plurality of (S-bend) waveguides 32, a multimode section 33 and an output waveguide 34. The multimode section 33 may be arranged such that light from the plurality of waveguides 32 is multiplexed into the output waveguide 34, e.g. by using the self-imaging effect as described with reference to Figure 2.

The electro-optical converters 31aa, 31ab, 31ba, 31bb may be light emitting apparatuses. The light emitting apparatuses may be light emitting diodes (LED) or lasers. The lasers may be distributed feedback laser (DFB) lasers. In particular, the lasers may be directly modulated lasers (DML) or lasers using electro-absorption modulation (EAM), i.e. so called Electro-Absorption Modulated Lasers (EML). The material used for such converters 31aa, 31ab, 31ba, 31bb may be semiconductor material, such as Gallium arsenide, indium phosphide, gallium antimonide, and gallium nitride.

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Fig. 3 shows an arrangement where serial multiplexing of wavelengths is used in addition to parallel multiplexing based on MMI multiplexing. As a result, a given number of CWDM wavelengths can be multiplexed onto an output waveguide 34 using smaller MMI multiplexers which have tolerable multiplexing losses. The serial multiplexing is achieved by placing in series two or more electro-optical converters 31aa, 31ab. The concept of serial multiplexing is outlined in the context of Fig. 4 which shows an embodiment of the converters 31aa, 31ab of Fig. 3.

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The converters 31aa, 31ab comprise different active materials configured to convert an electrical signal into an optical signal. Furthermore, the converters 31aa and 31ab comprise an optical waveguide 37 for confining the emitted optical signal. The optical waveguide 37 traverses the two converters 31aa, 31ab. In particular, the waveguide 37 traverses a first active material of the first converter 31aa and a second active material of the second converter 31ab. By electrically stimulating the first active material, light within a first wavelength interval (referred to as light at a first wavelength) may be emitted. By electrically stimulating the second active material, light within a second wavelength interval (referred to as light at a second wavelength) may be emitted. By electrically stimulating both active materials, light signals at the first wavelength and light signals

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at the second wavelength may be generated simultaneously within the waveguide 37, i.e. the light signals may be serially multiplexed onto the waveguide 37 of the converters 31aa, 31ab. Waveguide 37 may be connected to the waveguide 32a which corresponds to one of the waveguides 32 of the MMI multiplexer depicted in Fig. 3. The waveguide 37 may be a single-mode waveguide, even for the short wavelengths carried by the waveguide 37. In an embodiment, light emitted from the first and second active materials may be light of wavelengths in the wavelength interval of about 1450nm to about 1750 nm. By stimulating the active materials of converters 31aa, 31ab using a modulated electrical signal, modulated optical signals at a first and second wavelength, respectively, may be generated.

By the arrangement illustrated in Figs. 3 and 4, parallel and serial multiplexing of the light generated by the electro-optical converters, e.g. single-wavelengths CWDM emitters, may be used, in order to design multi-wavelength CWDM emitters with a large numbers of optical channels, i.e. with a large number of CWDM wavelengths. In particular, this kind of serial multiplexing is feasible in the context of CWDM because of the large wavelength difference between different CWDM channels, which reduces the optical crosstalk between channels which are serially multiplexed.

In view of the fact that the light at the first wavelength traverses the second converter 31ab, the second material used in the second converter 31ab is preferably selected such that light at the first wavelength passes through with low losses. Therefore, appropriate electro-optical materials for the first 31aa and the second 31ab converter may be selected. In an embodiment, the material of the first 31aa and second 31ab converter are selected such that the second wavelength is smaller than the first wavelength. In addition to designing the materials to emit a particular wavelength, the materials may be designed such that light at higher

wavelengths than the particular emitted wavelength passes through the electro-optical material unaffected. As such, the second material of the second converter 31ab may be designed to emit the second wavelength and it may be designed to not attenuate light at higher wavelengths than the
5 second wavelength (e.g. light at the first wavelength).

It should be noted that in addition to emitting light at the first wavelength, the material of the first converter 31aa may be selected such that light at the second wavelength, i.e. light at wavelengths which are lower than the
10 first wavelength, is absorbed.

The above conditions regarding the materials may be achieved by selecting appropriate compositions of electro-optical materials such as semiconductor materials comprising Indium (In), Gallium (Ga), Aluminium
15 (Al), Arsenide (As) and/or Phosphorous (P).

The first 31aa and second 31ab converter may comprise a first 36aa and a second 36ab grating, respectively, in order to provide DFB lasers. The first grating 36aa may have a grating period which allows for lasing at the first
20 wavelength. The first 36aa and second 36ab gratings may be implemented as periodic variations of the refractive index of the material of the converter waveguide 37. The periodic variations of the refractive index are illustrated in Fig. 4 by a periodic succession of black and white sections of converter waveguide 37. The first 36aa and second 36ab gratings may have
25 grating periods which allow for lasing at the first and second wavelength, respectively. Furthermore, the second grating 36ab may be transparent to the first wavelength.

In addition, the first 31aa and second 31ab converter may comprise a first
30 35aa and second 35ab rear reflector, respectively. The rear reflectors 35aa, 35ab may be configured to reflect the light emitted by the respective

converter 31aa, 31ab, i.e. the light at the first and second wavelength, respectively. Furthermore, the second rear reflector 35ab, i.e. the rear reflector of the second converter 31ab, may be configured to let pass (a high percentage, e.g. more than 50%, of) the light at the first wavelength.

5 The light at the first and second wavelengths travels downstream towards the waveguide 32a. As such, the backward crosstalk between the different wavelengths can be reduced. Furthermore, the overall efficiency of the lasers can be improved.

10 Figure 5 shows an example of a 4-to-1 MMI multiplexer and 4 pairs of serially multiplexed converters 31aa, 31ab. As such, a multi-wavelength CWDM emitter using parallel and serial multiplexing is illustrated. In the CWDM emitter according to Figure 5, 8 CWDM channels are multiplexed and the chip dimensions may be about $0.85 \times 3 \text{ mm}^2$. In the CWDM emitter which
15 uses only the 4-to-1 MMI multiplexer shown in Figure 2a, the dimensions were preferably about $0.85 \times 2.5 \text{ mm}^2$. That means that although the CWDM emitter according to Figure 5 multiplexes 8 channels, i.e. twice the number of channels that are multiplexed by the CWDM emitter shown in Figure 2, the number of devices per wafer may only decrease by 20%. Furthermore,
20 serial multiplexing does not substantially increase the multiplexing losses. As such, the use of serial multiplexing may limit the increase in dimension and multiplexing losses compared to the increase in dimension (typically 400%) and the increase in multiplexing losses which are encountered when using only parallel multiplexing (e.g. when moving from a 4 channel MMI
25 multiplexer to an 8 channel MMI multiplexer).

The different wavelengths generated by the converters 31aa, 31ab may be arranged such that the wavelength difference between serially multiplexed wavelengths is high. This can be achieved by selecting four neighbouring
30 wavelengths (1417nm, 1491nm, 1511nm, 1531nm) for parallel multiplexing and by serially multiplexing the following four wavelengths with the

respective other wavelengths (1551nm, 1571nm, 1591nm, 1611nm). This is illustrated in Fig. 5. By attributing the wavelengths to serial and parallel multiplexing in such a manner, the difference between wavelengths which are serially multiplexed can be maximized. In the present example, the
5 CWDM wavelengths are spaced by about 20 nm such that a large channel spacing of about 80 nm between adjacent serially multiplexed emitters can be achieved, thereby reducing the crosstalk.

As outlined above, the material of the different converters is preferably
10 selected appropriately. The material used for emitting light at about 1471 nm (resp. 1491nm, 1511nm and 1531nm), i.e. the material used for the second converter 31ab, may be transparent to the light at about 1551 nm (resp. 1571nm, 1591nm and 1611nm), i.e. to the light emitted in the first converter 31aa. By doing this, the multiplexing losses caused by the serial
15 multiplexing can be reduced. Furthermore, the material used for emitting light at about 1551 nm (resp. 1571nm, 1591nm and 1611nm), i.e. the material used for the first converter 31aa, could completely absorb the emission at about 1471 nm (resp. 1491nm, 1511nm and 1531nm), i.e. the light emitted in the second converter 31ab. By doing this, the backward
20 crosstalk could be reduced. Alternatively or in addition, a negatively biased section, or a reflector as outlined above, may be introduced between the adjacent converters 31aa and 31ab in order to further reduce the backward crosstalk.

25 It should be noted that while the two electro-optical converters 31aa, 31ab of Figs. 4 and 5 are illustrated for emitting and multiplexing light at two different wavelengths, the underlying principle of serial multiplexing may be extended to an arbitrary number of wavelengths. In general terms, a waveguide W 37 may traverse N serially concatenated converters C_n 31aa, 31ab emitting light at different wavelengths λ_n , $n=1, \dots, N$ (N being an
30 arbitrary integer value greater than one). Each wavelength λ_n belongs to a

different wavelength interval T_n , $n=1, \dots, N$. Without loss of generality, it is assumed that the different wavelength intervals T_n are ordered according to decreasing wavelengths, i.e. T_n comprises the lowest wavelengths and T_1 comprises the highest wavelengths.

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In order to emit the different wavelengths λ_n , the succession of converters C_n 31aa, 31ab comprises different active materials M_n , $n=1, \dots, N$, i.e. the waveguide W 37 traverses different active materials M_n . Each active material M_n may be configured to emit light at a wavelength λ_n belonging to the wavelength interval T_n , respectively. It is assumed that material M_N is positioned at the output end of the succession of converters C_n and that material M_1 is positioned at the input or rear end, opposite or upstream to the output end, of the serially connected converters C_n . In other words, material M_N is positioned at the output end of waveguide W 37 and material M_1 is positioned at the rear end of waveguide W 37. Each active material M_i is configured to leave unaffected light at a wavelength λ_j belonging to the wavelength interval T_j , for $j < i$. In addition, each active material M_i may be configured to absorb light at a wavelength λ_j belonging to the wavelength interval T_j , for $j > i$. As such, the light emitted by material M_i passes through materials $M_{i+1}, \dots, M_N$ without being attenuated, in order to reach the output end of the waveguide W 37. Consequently, the serial multiplexing can be performed with low multiplexing losses. On the other hand, the light emitted by material M_i which travels towards the rear end of the waveguide W 37, i.e. which travels towards materials $M_{i-1}, \dots, M_1$ will be absorbed, thereby reducing backward crosstalk.

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Optionally, the different regions and materials may be separated by different reflectors R_n , $n=1, \dots, N-1$, or negatively biased sections, in order to further reduce the crosstalk. The reflectors R_n may be placed at the rear end of a converter C_n . Each reflector R_n may be configured to reflect wavelengths λ_n from the wavelengths interval T_n . Furthermore, each

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reflector R_n may be configured to let pass wavelengths λ_j from the wavelengths interval T_j , for $j < n$. The same or other reflectors may be used for providing converters C_n which comprise laser cavities.

5 Above a serial connection of converters C_n has been described in more general terms. A plurality of K such serial groups of converters may be placed in parallel, i.e. K such serial connections of converters may be placed in parallel onto a PIC, as shown e.g. in Fig.5. As such, a matrix of converters C_{kn} with $n=1, \dots, N$ and $k=1, \dots, K$, is obtained wherein the
 10 converters C_{kn} for a particular value k are connected in series using a common waveguide W_k 37 as outlined above. The K output signals of the waveguides W_k 37 may be optically multiplexed using parallel multiplexing, e.g. MMI multiplexing or AWG multiplexing. As such a CWDM transmitter or emitter configured to generate and multiplex $K \cdot N$ wavelengths λ_{kn} , with
 15 $n=1, \dots, N$ and $k=1, \dots, K$ may be provided. The CWDM transmitter comprises K groups of converters C_{kn} , wherein the k^{th} group of converters provides N serially multiplexed optical signals at wavelengths λ_{kn} , $n=1, \dots, N$. As outlined above, the serial multiplexing may be achieved by selecting appropriate active materials M_{kn} .

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In order to reduce the crosstalk between the serially multiplexed wavelengths λ_{kn} , the wavelengths may be arranged within the matrix of converters C_{kn} such that for some or all pairs of neighboring converters C_{ki} , C_{ki+1} of a group of serial converters along waveguide W_k , there are $K-1$
 25 wavelengths λ_{kn} which are greater than wavelength λ_{ki+1} emitted by converter C_{ki+1} and smaller than wavelength λ_{ki} emitted by converter C_{ki} . In an embodiment, this may be achieved by arranging the converter within the matrix such that $\lambda_{kn} > \lambda_{in}$, for $k > i$, and $\lambda_{kn} > \lambda_{ki}$, for $i > n$.

30 Figure 6 shows an exemplary schematic view of an arrangement where three wavelengths are multiplexed in series in four groups 31a, 31b, 31c,

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31d of converters prior to performing parallel multiplexing using a 4-to-1 MMI multiplexer. As outlined in the context of Figs. 3 to 5, the MMI multiplexer may comprise a plurality of waveguides 32, a multimode section 33 and an output waveguide 34. The groups 31a, 31b, 31c, 31d of electro-optical converters comprise waveguides 37a, 37b, 37c, 37d which traverse the three converters 31aa-31ac, 31ba-31bc, 31ca-31cc and 31da-31dc, respectively. Each waveguide 37a, 37b, 37c, 37d traverses or passes through three different active materials, i.e. one active material per converter 31aa-31ac, 31ba-31bc, 31ca-31cc and 31da-31dc. As such, each group 31a, 31b, 31c, 31d of converters emits three multiplexed CWDM wavelengths which are subsequently multiplexed using a 4-to-1 MMI multiplexer.

In the present document a method and system of multiplexing light at different wavelengths has been described. In particular, a CWDM transmitter has been described which makes use of serial multiplexing of a plurality of wavelengths. In order to increase the distance between adjacent serially multiplexed wavelengths, and to thereby reduce the crosstalk, serial multiplexing may be combined with parallel multiplexing (e.g. using MMI multiplexers or AWG multiplexers). As a result, low cost and low loss CWDM transmitters may be provided. In particular, CWDM transmitters with a high degree of circuit integration may be provided. Such CWDM transmitters may be implemented as PICs for the use in optical access networks.

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It should be noted that the description and drawings merely illustrate the principles of the proposed methods and systems. It will thus be appreciated that those skilled in the art will be able to devise various arrangements that, although not explicitly described or shown herein, embody the principles of the invention and are included within its spirit and scope. Furthermore, all examples recited herein are principally intended expressly

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to be only for pedagogical purposes to aid the reader in understanding the principles of the proposed methods and systems and the concepts contributed by the inventors to furthering the art, and are to be construed as being without limitation to such specifically recited examples and
5 conditions. Moreover, all statements herein reciting principles, aspects, and embodiments of the invention, as well as specific examples thereof, are intended to encompass equivalents thereof.

Furthermore, it should be noted that any block diagrams herein represent
10 conceptual views of illustrative circuitry embodying the principles of the invention. Similarly, it will be appreciated that any flow charts, flow diagrams, state transition diagrams, pseudo code, and the like represent various processes which may be substantially represented in computer readable medium and so executed by a computer or processor, whether or
15 not such computer or processor is explicitly shown.

Claims

1. An optical transmitter configured to generate a plurality of optical signals at a corresponding plurality of different wavelengths multiplexed onto an output waveguide (34); the transmitter comprising:
 - a first (31aa) and second (31ab) converter comprising different first and second active materials configured to emit light at a first and a different second wavelength, respectively; and
 - a first converter waveguide (37a) traversing the first and second material of the first (31aa) and second (31ab) converter, the second material being at an output end of the first converter waveguide (37a) and the first material being at an input end, upstream of the output end, of the first converter waveguide (37); wherein the second active material is transparent to the light at the first wavelength; wherein the output end of the first converter waveguide (37a) is coupled to the output waveguide (34).
2. The optical transmitter of claim 1, wherein the first active material is configured to absorb the light at the second wavelength and wherein the second wavelength is smaller than the first wavelength.
3. The transmitter of any previous claim, wherein the first converter (31aa) comprises a first laser using the first active material and wherein the second converter (31ab) comprises a second laser using the second active material.
4. The transmitter of any previous claim, wherein the first converter (31aa) comprises a first grating (36aa) at a first grating period associated with the first wavelength, and wherein the second converter

(31ab) comprises a second grating (36ab) at a second grating period associated with the second wavelength.

5. The transmitter of any previous claim, further comprising:

- 5 – a semitransparent reflector (36ab) positioned at an output end of the first converter (31aa) and at an input end of the second converter (31ab), the semitransparent reflector (36ab) being substantially reflective to light at the second wavelength.

10 6. The transmitter of any previous claim, wherein

- the first and second material are semiconductor materials from a group of materials comprising Gallium, Indium, Aluminium, Phosphorous and/or Arsenide; and
- the transmitter is a photonic integrated circuit.

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7. The transmitter of any previous claim, wherein the transmitter is an optical coarse wavelength division multiplexing transmitter.

8. The transmitter of any previous claim, wherein

- 20 – the transmitter comprises K groups (31a, 31b, 31c, 31d) of N converters C_{kn} , $k=1,\dots,K$ and $n=1,\dots,N$ with $K>1$ and $N>1$; each group configured to generate a serially multiplexed optical signal S_k comprising N optical signals at wavelengths λ_{kn} , $n=1,\dots,N$ multiplexed onto a converter waveguide W_k ;
- 25 – the converters C_{kn} comprise different active materials M_{kn} configured to emit light at the wavelength λ_{kn} , respectively;
- the first (31aa) and second (31ab) converter correspond to the converters C_{11} and C_{12} , respectively;
 - the first and second active materials correspond to the materials
- 30 M_{11} and M_{12} , respectively;

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- the first converter waveguide (37a) corresponds to the converter waveguide W_1 of the first group of N optical converters C_{1n} ;
- the converter waveguides W_k , $k=1, \dots, K$, traverse the N active materials M_{kn} , $n=1, \dots, N$ of the k^{th} group of optical converters; material M_{kN} being at an output end of the waveguide W_k and material M_{k1} being at an input end, upstream of the output end, of the waveguide W_k ;
- material M_{ki} is configured to be transparent to light at a wavelength λ_{kj} with $j < i$; and
- material M_{ki} is configured to absorb light at a wavelength λ_{kj} with $j > i$; and
- the transmitter comprises an optical combiner (32, 33) configured to multiplex the K serially multiplexed optical signals S_k at the output end of the K converter waveguides W_k onto the output waveguide (34).

9. The transmitter of claim 8, wherein

- the converters C_{kn} comprise gratings G_{kn} at grating periods Λ_{kn} , respectively;
- the first (36aa) and second (36ab) gratings correspond to the gratings G_{11} and G_{12} , respectively; and
- the grating periods Λ_{kn} are associated with the wavelengths λ_{kn} of the light emitted by the corresponding converters C_{kn} .

10. The transmitter of any of claims 8 to 9, wherein

- the K groups of converters C_{kn} are laterally spaced with respect to one another such that the output end of the K combiner waveguides W_k are at a lateral distance with respect to one another;

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- the combiner comprises a first merging section (32), where the lateral distance between the K combiner waveguides W_k is progressively reduced; and
- the combiner comprises a second merging section (33), where the serially multiplexed optical signals S_k are superimposed within a joint waveguide leading to the output waveguide.

11. The transmitter of claim 10, wherein the first merging section (32) comprises a plurality of S-bend waveguides configured to progressively reduce the distance between the K combiner waveguides W_k .

12. The transmitter of any of claims 8 to 11, wherein the combiner (32, 33) is a multimode interference multiplexer.

13. The transmitter of any of claims 8 to 12 wherein the active materials M_{kn} and the corresponding wavelengths λ_{kn} are arranged such that for at least one pair of neighboring converters C_{ki} , C_{ki+1} of the k^{th} group of converters along the combiner waveguide W_k , there are $K-1$ wavelengths of the set of wavelengths λ_{kn} , $k=1, \dots, K$ and $n=1, \dots, N$, which are greater than wavelength λ_{ki+1} emitted by converter C_{ki+1} and smaller than wavelength λ_{ki} emitted by converter C_{ki} .

14. The transmitter of claim 13, wherein the active materials M_{kn} and the corresponding wavelengths λ_{kn} are arranged such that $\lambda_{kn} > \lambda_{in}$, for any $k > i$, and $\lambda_{kn} > \lambda_{ki}$, for any $i > n$.

15. A method for generating a plurality of optical signals at a corresponding plurality of different wavelengths multiplexed onto an output waveguide; the method comprising:

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- providing a first (31aa) and second (31ab) converter comprising different first and second active materials configured to emit light at a first and a different second wavelength; and
- providing a first converter waveguide (37a) traversing the first and second material of the first (31aa) and second (31ab) converter, the second material being at an output end of the first converter waveguide (37a) and the first material being at an input end, upstream of the output end, of the first converter waveguide (37a); wherein the second active material is transparent to the light at the first wavelength; wherein the output end of the first converter waveguide (37a) is coupled to the output waveguide (34).