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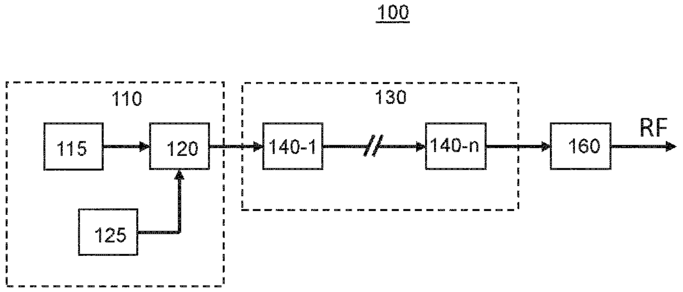

Figure 1

(57) Abstract: Embodiments described herein relate to methods and apparatus for generating a radio frequency (RF) signal generator using optical processing. In an embodiment an RF signal generator (100) comprises an optical comb generator module (110) arranged to provide a plurality of spectral components at spaced wavelengths, an optical filter module (130) coupled to the optical comb generator module (110) and an optical-to-electrical converter device (160). The optical filter module (130) comprises a plurality of interferometer devices (140-1 - 140n) coupled in series. Each interferometer device is arranged to remove a respective set of spectral components from the plurality of spectral components in order to output predetermined spectral components from the optical filter module (130) to the optical-to-electrical converter device (160), the predetermined spectral components being a subset of the plurality of spectral components. The optical-to-electrical converter device (160) is arranged to heterodyne the predetermined spectral components to generate a radio frequency signal.

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RADIO FREQUENCY SIGNAL GENERATION

Technical Field

Embodiments disclosed herein relate to methods and apparatus for generating radio frequency (RF) signals, which may be used in wireless communications systems.

Background

The third-generation partnership (3GPP) is currently working on standardization of Fifth Generation New Radio (5G NR) technologies. The spectrum of 5G and next-generation radio includes Extremely High-Frequency range (30-300GHz), also known as the mmW domain. Generating accurate and stable radio frequency (RF) signals is increasingly important for such systems, however current solutions suffer from noise, inaccuracies and insufficient stability.

Current solutions for the generation of RF carriers are commonly based on the use of synthesizers which produce the desired frequency by multiplying a reference frequency from a local oscillator, in a Phase-Locked Loop (PLL) circuit. The PLL comprises a phase detector that returns a signal that is proportional to the phase difference of the input reference frequency f_{IN} and the output frequency f_{OUT}. A loop filter is coupled to the output of the phase detector and is a low pass filter that reduces jitter in case of noisy inputs and selects the desired phase difference. The output of the loop filter is a voltage which is used to control a voltage controlled oscillator (VCO) so that it generates an oscillating electrical signal. The VCO is forced to settle on a value that matches the long-term average of the input frequency. The value of “long term average” is determined by the characteristics of the loop components, including the low-pass filter.

Oscillators are one of the main building blocks in the communication system. Their role is to create stable reference signals for frequency and timing synchronization. Any real oscillator suffers from hardware imperfections that introduce phase noise (PN) to the communication system. PN is the instantaneous deviation of the phase from the ideal value. The fundamental source of the PN is the inherent noise of the passive and active components noise inside the oscillator circuitry: thermal noise, white noise (uncorrelated) and ‘coloured noise’ (correlated, e.g. flicker noise).

Oscillator phase noise (PN) is one of the hardware imperfections that is becoming a limiting factor in high data rate digital communication systems. PN is determined by random deviations of the phase value that cause a leakage of the channel power out of its designated BW. The negative effect of phase noise is more pronounced in high carrier frequency systems, e.g., E-band (60-80 GHz), mainly due to the high level of PN in oscillators designed for such frequencies. Moreover, PN severely affects the performance of multiple-input-multiple-output (MIMO) systems. PN also affects the orthogonality of the subcarriers in OFDM-based transmission systems that degrade the performance by producing intercarrier interference.

Additionally, there are deviations of the phase occurring on a longer timescale and causing jitter on a frequency that is close to the channel. These deviations are indicated as ‘wander’, as the part of phase noise that is within 10 Hz from the carrier BW. Current synthesizers based on PLL and phase detectors face the problem of the jitter caused by phase noise. Fluctuation caused by wander might be challenging to filter out in a PLL since it would require a very narrow filter: solutions to avoid cumulating wander, commonly consist in using First In First Out (FIFO) buffer to absorb the momentary discrepancies. Using FIFO is effective since wander causes low-frequency differences; however, this introduces some latency which may not be acceptable depending on the application scenarios.

Summary

According to certain embodiments described herein there is provided a radio frequency generator comprising an optical comb generator module arranged to provide a plurality of spectral components at spaced wavelengths, an optical filter module coupled to the optical comb generator module and an optical-to-electrical converter device. The optical filter module comprises a plurality of interferometer devices coupled in series. Each interferometer device is arranged to remove a respective set of spectral components from the plurality of spectral components in order to output predetermined spectral components from the optical filter module to the optical-to-electrical converter device. The predetermined spectral components are a subset of the plurality of spectral components. The optical-to-electrical converter device is arranged to heterodyne the predetermined spectral components to generate a radio frequency signal.

Certain embodiments allow for the generation of RF signal which reduce or eliminate many of the causes of phase noise thereby providing a stable low noise RF signal even at the higher frequencies being demanded by new wireless communications technologies such as 5G New Radio. The use of photonic generation means that the generated RF signal is more accurate, less noisy and more stable. The RF signal can be carried optically over long distances before conversion into an electrical RF signal which eliminates the electromagnetic interference that an electrical RF signals would otherwise be subject to.

According to certain embodiments described herein there is provided a method of generating a radio frequency signal. The method comprises generating a plurality of spectral components at spaced wavelengths by acting on an optical input signal and filtering the plurality of spectral components using a series of interferometer devices arranged to remove respective sets of spectral components in order to output predetermined spectral components. The predetermined spectral components are heterodyned in order to generate the radio frequency signal.

Certain embodiments also provide corresponding computer programs and computer program products.

Brief Description of Drawings

For a better understanding of the embodiments of the present disclosure, and to show how it may be put into effect, reference will now be made, by way of example only, to the accompanying drawings, in which:

Figure 1 is a schematic diagram illustrating a radio frequency (RF) signal generator according to some embodiments;

Figure 2 is a schematic diagram illustrating an interferometer device according to some embodiments;

Figure 3 is a schematic diagram illustrating filtering of optical spectral components using interferometer devices according to an embodiment;

Figure 4 is flow diagram illustrating a method of generating an RF signal according to some embodiments;

Figure 5 is a schematic diagram illustrating the architecture of a wireless communications system according to some embodiments.

Figure 6A-C illustrating fields of interference of optical spectral components according to some embodiments; and

Figure 7 illustrates successive removal of optical spectral components according to some embodiments.

Detailed Description

Generally, all terms used herein are to be interpreted according to their ordinary meaning in the relevant technical field, unless a different meaning is clearly given and/or is implied from the context in which it is used. All references to a/an/the element, apparatus, component, means, step, etc. are to be interpreted openly as referring to at least one instance of the element, apparatus, component, means, step, etc., unless explicitly stated otherwise. The steps of any methods disclosed herein do not have to be performed in the exact order disclosed, unless a step is explicitly described as following or preceding another step and/or where it is implicit that a step must follow or precede another step. Any feature of any of the embodiments disclosed herein may be applied to any other embodiment, wherever appropriate. Likewise, any advantage of any of the embodiments may apply to any other embodiments, and vice versa. Other objectives, features and advantages of the enclosed embodiments will be apparent from the following description.

The following sets forth specific details, such as particular embodiments or examples for purposes of explanation and not limitation. It will be appreciated by one skilled in the art that other examples may be employed apart from these specific details. In some instances, detailed descriptions of well-known methods, nodes, interfaces, circuits, and devices are omitted so as not obscure the description with unnecessary detail. Those skilled in the art will appreciate that the functions described may be implemented in one or more nodes using hardware circuitry (e.g., analog and/or discrete logic gates interconnected to perform a specialized function, ASICs, PLAs, etc; and photonics integration) and/or using software programs and data in conjunction with one or more digital microprocessors or general purpose computers. Nodes that communicate using the air interface also have suitable radio communications circuitry. Moreover, where appropriate the technology can additionally be considered to be embodied entirely within any form of computer-readable memory, such as solid-state memory, magnetic disk, or optical disk containing an appropriate set of computer instructions that would cause a processor to carry out the techniques described herein.

Hardware implementation may include or encompass, without limitation, digital signal processor (DSP) hardware, a reduced instruction set processor, hardware (e.g., digital or analogue) circuitry including but not limited to application specific integrated circuit(s) (ASIC) and/or field programmable gate array(s) (FPGA(s)), and (where appropriate) state machines capable of performing such functions. Memory may be employed to storing temporary variables, holding and transfer of data between processes, non-volatile configuration settings, standard messaging formats and the like. Any suitable form of volatile memory and non-volatile storage may be employed including Random Access Memory (RAM) implemented as Metal Oxide Semiconductors (MOS) or Integrated Circuits (IC), and storage implemented as hard disk drives and flash memory. Photonic integration may include photonics circuits or modules utilising, without limitation, Silicon on Insulator (SOI) and/or Silicon Nitride (SiN) platforms. Any reference to a module may alternatively refer to a device, system, apparatus, or the apparatus itself without reference to a module. For example, references to an optical filtering module may be replaced with references to an optical filter or a plurality of interferometers.

Embodiments described herein relate to generating one or more RF signals using optical signal processing and may include photonics integration. In some embodiments, coherent harmonics of an optical input signal are generated, for example using an optical comb generator, and a series of interferometer devices are used to remove some of these harmonics using destructive interference. The remaining harmonics are heterodyned and the difference or beat signal converted into the electrical domain in order to generate the RF signal. The resulting electrical RF signal has low phase noise compared with current approaches to RF signal generation.

Figure 1 illustrates an RF signal generator according to an embodiment. The RF generator 100 comprises an optical comb generator 110 coupled to an optical filtering module 130 which is coupled to an optical-to-electrical conversion device 160. The optical comb generator 110 comprises a phase modulator 120 which acts on an optical input signal from an optical source 115 such as a continuous wave laser (CWL). The phase modulator 120 acts on the optical signal using modulating signal provided by a modulating signal generator 125. The output of the phase modulator is a plurality of spaced optical spectral components corresponding to harmonics of the modulating signal. Any other suitable optical comb generator may alternatively be employed, for example a micro-comb generator exploiting nonlinear Kerr effects and directly modulated-lasers.

The optical filtering module 130 comprises a plurality of interferometer devices 140-1 to 140-n coupled together in series. The interferometer devices may comprise unbalanced Mach-Zehnder Interferometers (MZI), although other interferometer device types may alternatively be used. Each interferometer device is arranged to remove a respective set of spectral components from the plurality of spectral components such that predetermined spectral components are output to the optical-to-electrical converter device 160.

Two of the predetermined spectral components may be heterodyned and their difference or beat signal converted into the electrical domain by the optical-to-electrical converter device 160. This difference or beat signal is the wanted RF signal. Where more than two predetermined spectral components are present, the optical-to-electrical converter device 160 may be configured with a limited bandwidth that does not convert to the electrical domain any beat signals that could arise with the other predetermined spectral components. The optical-to-electrical conversion device 160 may be a photodetector such as a photodiode, travelling wave photodetector or any other suitable component.

The above described optical components (115, 120, 130, 160) of the RF generator may be implemented using photonic modules and may be integrated into a single device. In another example, all but the optical-to-electrical converter device 160 is integrated into a single photonic device and the optical-to-electrical converter device 160 is coupled using a waveguide in order to allow this to be located remotely from the rest of the RF generator. For example the optical-to-electrical converter device 160 may be located adjacent electrical communications circuitry in order to reduce electromagnetic interference to the RF signal that might otherwise occur if this way carried over a distance in the electrical domain. The waveguide may be an optical fibre or an integrated waveguide in an integrated silicon photonic chip.

In order to enhance understanding, the CWL 115 may be configured to provide an optical input signal to the phase modulator 120 having a frequency of 190000GHz (190THz). The modulation signal generator 125 may be configured to provide an electrical modulation signal having a frequency of 10GHz. The optical phase modulator 120 may be configured to generate optical spectral components at 190THz (harmonic number N=0), 190THz+10GHz (N=1), 190THz-10GHz (N=-1), 190THz+20GHz (N=2), 190THz-20GHz (N=-2), 190THz+30GHz (N=3), 190THz-30GHz (N=-3), 190THz+40GHz, 190THz-40GHz (N=-4), etc. The number and relative amplitude of the harmonics generated will depend on the configuration of the phase modulator 120. Single sided harmonics may be employed (i.e. N=0, 1, 2, 3, etc), for example using an optical filter. The comb generator 110 therefore generates a plurality of optical spectral components at spaced wavelengths; that is non-zero amplitude optical radiation at the wavelength of the input optical signal and at wavelengths spaced therefrom by harmonics of the modulating signal. Zero amplitude may be considered the noise floor.

The interferometer devices 140-1 to 140-n are arranged to remove some spectral components by causing different optical propagation delays to the spectral components passing through such that the removed spectral components destructively interfere whilst the remaining spectral components constructively interfere. An embodiment of an interferometer device is shown in Figure 2. The interferometer device 240 comprises a coupler 242, two branches 245A, 245B and a combiner 247.

The coupler has an input port 242i and two output ports 242o1, 242o2 and is configured to evenly split optical radiation corresponding to spectral components received at the input port 242i to the two output ports 242o1, 242o2. The coupler may be a directional coupler or a multi-mode interferometer although other coupler types may alternatively be employed.

The output ports 242o1, 242o2 of the coupler 242 are coupled to respective branches 245A, 245B of the interferometer device 240. The two branches 245A, 245B are waveguides which cause different optical propagation delays to the spectral components passing through them. This may be achieved by changing the refractive index in the waveguide of one or both branches. For example, a control element 250 such as a heater adjacent a portion of one branch 245B may be used to adjust the refractive index of this portion in order to provide the desired different in optical propagation delay between the two branches. The refractive index may be adjusted using the thermo-optic effect for example. A fine controller 255 may also be employed to adjust the optical propagation delay in one branch 245A (or both branches) in order to compensate for practical implementation effects such as thermal drift of the refractive index.

The combiner 247 comprises two input ports 247i1, 247i2 each coupled to a respective branch 245A, 245B. The combiner 247 also comprises at least one output port 247o1, 247o2. The output ports 247o1, 247o2 select or output a respective interference field; in the case of two output ports, the interference fields are complimentary. For example, one output port 247o2 is configured to output the sum (A+B) of the two branch inputs 247i1, 247i2 whilst the other output port 247o1 is configured to output the “subtraction” of the two branch inputs 247i1, 247i2 (A-B). The two ports are configured to collect complementary interference patterns which exist at different points in space. This arrangement corresponds to setting a phase shift of $\frac{\pi}{2}$ in the electromagnetic field at port 247o2 with respect with the electromagnetic field at port 247o1. This means that if the difference in optical propagation delays causes a subset X of a set of spectral components to destructively interfere, the other spectral components, subset Y, will constructively interfere. In this case the “adding” (A+B) output port 247o2 will output subset Y and the “subtracting” (A-B) output port 247o1 will output subset X.

By using different combinations of series coupled interferometer devices 240, each with their own difference in optical propagation delay, a number of spectral components may be removed from the plurality of spectral components generated by the optical comb generator 110. By coupling subsequent interferometer devices 240 to a particular output port 247o1, 247o2 of the preceding interferometer device 240, the spectral components remaining may be further configured.

The combiner 247 may be a multimode interferometer or a directional coupler, although other combiner types could alternatively be employed.

Figure 3 shows an RF generator according to an embodiment using three interferometer devices. A CWL 315 is coupled to a phase modulator 320 which in turn is coupled to an optical filtering module 340. The optical filtering module 340 has three Mach-Zehnder Interferometers (MZI) 340-1, 340-2, 340-3 coupled in series, with the last MZI 340-3 coupled to a photodiode 360.

The phase modulator 320 or more generally an optical comb generator receives an optical signal from the CWL 315 or other optical source. A detail illustrates the optical signal as a spectral component in the frequency domain. The phase modulator also receives an electrical modulating signal having frequency *fm* from a modulating signal generator (not shown). The frequency domain of the phase modulator output illustrates a plurality of spectral components, spaced at harmonics of the modulating signal frequency *fm* from the optical signal frequency or wavelength. For example, where the optical signal is at 190THz and the modulating signal is at 10GHz, the plurality of spectral components would be at 190THz+10GHz, 190THz-10GHz, 190THz+20GHz, 190THz-20GHz, 190THz+30GHz, 190THz-30GHz, 190THz+40GHz, 190THz-40GHz, etc. That is the output of the phase modulator is a plurality of optical spectral components at spaced wavelengths, in this case spaced by 10GHz from each other and at multiples of 10GHz from the fundamental or wavelength of the optical signal.

The first MZI 340-1, coupled to the output of the phase modulator 320, removes some of these spectral components – these are illustrated in the upper frequency domain detail, whilst the retained or passed spectral components are illustrated in the lower frequency domain detail. The retained or non-filtered spectral components from the first MZI 340-1 are passed to the input of the second MZI 340-2 which removes some of these before passing the retained spectral components to the third MZI 340-3. The spectral components removed by the second MZI 340-2 are illustrated in the upper frequency domain detail and the retained spectral components are illustrated in the lower frequency domain detail. In this embodiment, the output from the first and second MZI 340-1, 340-2 use the adding output port 247o2 of their respective combiners 247.

The output of the second MZI 340-2 is coupled to the input of the third MZI 340-3. The output of the third MZI 340-3 uses a “subtracting” output port 247o1 of its combiner 247 in order to remove the fundamental spectral component (harmonic order 0^{th}). This is shown in the upper frequency domain detail with the remaining spectral components output to the photodiode 360 and illustrated in the lower frequency domain detail.

In this example only two spectral components are retained at the output of the optical filtering module 340. These predetermined or wanted spectral components are spaced apart by a multiple of the wavelength of the modulating signal, *Nfm* where N is the difference between the harmonic orders of the predetermined wavelengths. In the general case of an arbitrary number M of interferometers, $N=2^M$ so that the harmonic spacing between the retained harmonics is 2^M apart. In the example above where *fm*=10Ghz and M=3, $N=2^3=8$ so that the predetermined spectral components will be 8x*fm* or 80GHz apart.

The predetermined spectral components are input to the photodiode 360 which heterodynes them to generate a difference or beat signal. In the example above the difference signal will be at 80GHz. Heterodyning results in other signals including the frequencies of the spectral components themselves as well as the sum of the spectral components frequencies however the photodiode 360 will normally have a bandwidth that is only capable of converting the difference or beat signal into the electrical domain. The other higher frequency signals will be filtered out by the photodiode 360. The converted electrical difference or beat signal can then be used as the wanted RF signal.

Where spectral components corresponding to a larger number of harmonics of the modulating frequency are generated by the phase modulator, for example 10, and these are not filtered out by using additional interferometer devices, then they may instead be filtered out by the limited bandwidth of the photodiode 360. This is because their beat signals will be at higher frequencies than the lowest frequency beat signal corresponding to the most closely spaced spectral components.

Figures 6A-C illustrate in the time domain operation of the series of interferometer devices in more detail, with respect to one example configuration in which the relative delays of a sequence of three series coupled MZI are 0.5T (T/2), 0.25T (T/4) and 0.125T (T/8) where T is the period of the modulating signal *fm*. For example, where fm=10GHz T=100ps, T/2=50ps, T/4=25ps and T/8=12.5ps.

Figure 6A illustrates the effect of a relative optical propagation delay of 0.5T on various optical spectral components at the first MZI 340-1. The optical signal or fundamental spectral component (harmonic order N=0) is not shown to scale compared with the modulated spectral components. The first modulated spectral component (N=1) is the fundamental frequency (e.g. 1.9THz) modulated at the modulating signal frequency (e.g. 10GHz), that is the positive first harmonic N=1 (1.9THz+10GHz). The negative first harmonic N=-1 (1.9GHz-10GHz) is also illustrated. These waveforms have a period of T, the same as the modulating signal. The first MZI is arranged to cause a relative delay between spectral components of 0.5T, which will result in combining the two waveforms shown.

As can be seen, when added together, these two waveforms will cancel each other, effectively removing them from the “adding” output 247o2 of the first MZI 340-1. If the “subtracting” output 247o1 were used, then a complimentary output would be obtained, that is this harmonic N=1, N=-1 would be retained.

The subsequent harmonics N=2 to N=6 are illustrated as positive harmonics only for simplicity. Also for simplicity, only 6 harmonics are shown though the number of harmonics may vary depending on the configuration of the optical comb generator. Waveform N=2 corresponds to the optical carrier (N=0) being modulated by twice the modulating frequency resulting in a spectral component at 190THz+20GHz (and also 190THz-20GHz were we to also consider the corresponding negative harmonic N=-2). As can be seen, when the N=2 waveform in one branch is delayed by 0.5T compared with the N=2 waveform in the other branch of the MZI, the two waveforms interfere or add together constructively, that is their positive and negative portions are aligned in time and not 180 degrees out of phase as was the case with the N=1 (or N=-1) waveforms.

More generally it can be seen that with a differential delay of 0.5T, the odd harmonics N=1, 3, 3 destructively interfere whilst the even harmonics constructively interfere. This means that spectral components corresponding to the odd harmonics are removed from the first MZI 340-1 whilst the even harmonics are retained and passed on to the input of the second MZI 340-2. This result could be reversed by using the “subtracting” port 247o1 of the interferometer device instead of its “combining” output 247o2. In this case, spectral components corresponding to the even harmonics N=2, 4, 6 would be removed and spectral components corresponding to the odd harmonics N=1, 3, 5 would be retained and passed on to the input of the second MZI 340-2.

Figure 6B illustrates the effect of a relative delay of 0.25T in an interferometer device 340-2.

Considering for the moment only the waveforms retained from the first interferometer device 340-1 (that is N=2, 4, 6), it can be seen that the delayed N=2 waveforms will destructively interfere with each other and so would be removed from the output of the second interferometer device. Similarly, delayed N=6 waveforms destructively interfere. On the other hand, delayed N=4 waveforms constructively interfere. The result of this is that the combination of the first and second interferometer devices removes spectral components corresponding to the harmonics N=1, 2, 3, 5, 6 of the modulating signal, and retains spectral components corresponding to harmonic N=4 of the modulating signal. When considering both the positive and negative harmonics, this results in spectral components corresponding to N=-4 and +4, or 1.9THz-40GHz and 1.9THz+40GHz. The fundamental N=0 or 1.9THz is also retained.

Figure 6C illustrates the effect of a relative delay of 0.25T in an interferometer device 340-3. Considering for the moment only the waveforms retained from the first and second interferometer devices 340-1, 340-2 (that is N=4), it can be seen that the delayed N=4 waveforms will destructively interfere with each other and so would be removed from the "adding" output of the second interferometer device. Some higher order (more than N=6) harmonics may be retained where these exist. However, by using the "subtracting" output 247o1, the spectral component of the N=4 wavelength is retained and passed on to the photodiode 360. The "subtracting" output does remove the fundamental spectral component N=0.

Whilst the embodiment uses three series coupled MZI with a sequence of differential delays of T/2, T/4 and T/8, this order may be changed. As the MZI are linear devices the end result of the combination of MZI will be the same. The first MZI 340-1 may output some intermediate components but these will be filtered out downstream. For example, if the first MZI had a relative delay of 0.25T, referring to Figure 6B, it can be seen that spectral components corresponding to waveforms N=2 and N=6 destructively interfere whilst those corresponding to waveforms N=4 constructively interfere. However, waveforms N=1, 3, 5 partly constructively interfere and partly destructively interfere. For example, it can be seen that the waveform N=1 will have a reduced ON duty cycle, 0.25 instead of 0.5 and an extended OFF duty cycle 0.75. However due to subsequent relative delays for this modified N=1 waveform in subsequent MZI, this will be removed.

Therefore, alternative relative delay sequences may include T/8+T/4+T/2, T/4+T/8+T/2, T2+T/8+T/4 etc. In other examples four or more MZI may be employed, for example where there are a greater number of spectral components included in the output of the phase modulator. Similarly, only two MZI may be employed for a reduced number of spectral components output from the phase modulator. In another alternative, the MZI 340-3 may be omitted and the output frequency can be halved from *Nxfm* to *N/2xfm* by using the photodiode's limited bandwidth. Also, by swapping the combiner outputs 247o1, 247o2 coupled to downstream MZI, predetermined spectral components can be selected by appropriate configuration of the optical filtering module. These predetermined spectral components are then heterodyned and converted to the electrical domain to generate a wanted RF signal. The frequency of the RF signal may be adjusted by controlling the frequency of the modulating signal, for example where the optical filtering module 140, 340 is configured to select spectral components corresponding to harmonics N=-4 and N=4, by changing the frequency of the modulating signal from 10GHz to 9GHz, the RF signal will change frequency from 4x2x10GHz=80GHz to 4x2x9GHz=72GHz.

In general, for a modulating frequency *fm* and *M* series coupled interferometer devices, an optical comb with spectral spacing of $fm*(2^M)$ is obtained. In the previous example, where *fm* = 10GHz and M=3, a spacing of 10*8=80GHz is obtained. Were a further interferometer device to be added (M=4), the spacing between the selected or predetermined spectral components would be 10*16=160GHz. It can therefore be seen that adding an interferometer device 340-n to optical filtering module 340 doubles the spacing between the predetermined spectral components. In other words, each interferometer device removes one of two adjacent harmonics. With an initial 6 positive and negative harmonics, using three interferometer devices only two spectral components are selected and reach the optical to electrical converter 360.

Figure 7 illustrates removal of spectral components at the fundamental frequency *fo* +/- harmonics of the modulating frequency *fm*. Here the N=+/-1 and N=+/-3 are removed at the first MZI and N=+/-3 are removed at the second MZI. The third MZI removes the fundamental *fo* leaving only the two spectral components corresponding to N=+/-4 which are separated by *8xfm* and which are then heterodyned to generate the RF signal.

Thus, the interferometers function to remove different ones of the spectral components, i.e. using destructive interference. The different configurations of the interferometers, e.g. different delays introduced by the interferometer, provides for a cumulative removal of particular spectral components. The remaining spectral components have a frequency separation corresponding to the required RF signal frequency.

Figure 4 illustrates a method according to an embodiment. The method 400 may be implemented on the RF generators 100 or 300 of Figure 1 or 3, or using different hardware. The hardware may include discrete optical and electrical components or circuits, or may be implemented using integrated photonics.

At step 405, the method generates a plurality of coherent optical spectral components at spaced wavelengths by acting on an optical signal. The optical signal may be generated by a CWL or other means, and may be acted on by a phase modulator to generate other spectral components spaced at multiples of the wavelength of a modulating signal input to the modulator. However other methods of generating the plurality of spectral components may alternatively be used.

At step 410, the method filters the plurality of spectral components using a series of interferometer devices arranged to remove respective subsets of spectral components from the plurality of spectral components in order to output predetermined spectral components. The predetermined spectral components are a subset of the plurality of spectral components generated by a comb generator for example, and may be reduced to two such spectral components. The interferometers are arranged to cause destructive interference of some spectral components by introducing a differential optical propagation delay to the spectral components traveling down different branches of the interferometer. By configuring each interferometer device with different differential delays, different sets of spectral components destructively interfere, thereby removing them, whilst other sets of spectral components constructively interfere and so pass through to the next interferometer device. The non-filtered spectral components remaining at the output of the last interferometer in the series are the predetermined spectral components. These correspond to predetermined harmonics of the modulating signal, depending on the configuration of the interferometers including their respective differential delays and the interference pattern selected by their respective output ports – for example adding the optical fields from the branches or “subtracting” the said optical fields as previously described.

At step 415, the selected or predetermined spectral components are heterodyned to generate a radio frequency signal. The radio frequency signal is the difference or beat signal between the selected spectral components. An optical to electrical converter such as a photodiode may be used to heterodyne the selected spectral components. The optical to electrical converter also converts the beat signal into the electrical domain where the RF signal can be further processed. The photodetector’s limited bandwidth can also be used to filter out any other optical signals.

The frequency of the modulating signal can be controlled to control the spacings of the spectral components generated by the phase modulator, and therefore the frequency of the beat signal.

In a further embodiment, multiple RF signals at different frequencies may be generated using the same initial spectral components. This embodiment is illustrated in Figure 5. A communications system is illustrated and comprises an RF generator photonics circuit 500 comprising a phase modulator 520 coupled to a plurality of optical filter modules 530 which are themselves coupled to respective, or a common, photodetector.

The phase modulator 520 receives an optical input signal 517 and generates a plurality of spectral components 522 which are output to a plurality of optical filter modules 530. Each optical filter module 530 comprises a series of interferometer devices as previously described. However, each series is configured differently in order to select different subsets 533 of the plurality of spectral components. For example, one optical filter module may select spectral components corresponding to N=+/-4 whereas another optical filter module 530 selects for N=+/-8 or N=+/-16 – that is the spacing doubles with each additional optical filter module. This allows for different configurations to obtain the same RF signal. For example, to obtain 120GHz, either of the following two configurations may be employed: 1) 120/8=15GHz using *fm*=15GHz and M=3; 2) 120/16=7.5GHz using *fm*=7.5GHz and M=4. Using the previous example frequencies, this would result in spacings of 8xfm and 12xfm which correspond to beat signals of 80GHz and 120GHz respectively. The different sets of spectral components 533 are then heterodyned and converted into the electrical domain to generate respective RF signals 562. In some examples, the heterodyning generates only one RF signal, or is filtered to output only one RF signal. The one or more RF signals 525 may optionally then be processed electrically by communications processing circuitry 580, for example to generate one or more LTE or 5G New Radio or 6G radio frequency signals for transmission by an antenna array 585. The transmitted radio signals 587 then travel over an air-interface to enable wireless communications with wireless devices (user devices).

This embodiment enables the generation of a number of low phase noise RF signals from coherent optical signals. This improves the accuracy and stability of RF signals generated for use in high frequency communications systems.

Whilst embodiments have been described in the context of generating RF signals for use in communications systems, other applications are also possible. For example, THz spectroscopy, radio-over-fibre or any other application requiring a common high frequency clock. For example, radio-over-fibre may deliver a radio signal to remote transceivers for implementing coherent multiple-input-multiple-output (MIMO) processing.

The embodiments provide a number of advantages. An RF signal is generated that has a reduced amount of phase noise compared with known RF generation methods, due to the photonic generation method that exploits the beat signal of two harmonics in a carrier characterized by high coherence.

In an embodiment, an oscillator is used to generate a modulating signal for an optical phase modulator which outputs a multiple of the oscillator frequency without the use of a synthesizer and a complex PLL loop. The amount of phase noise depends on the original oscillator only.

In embodiments the output RF signal is generated though photo-detection of beating between two optical harmonics originated by nonlinear electro-optical modulation of an optical carrier by the input modulating signal frequency. This generation method allows carrying the RF signal over the optical carrier from the generation point to the photodetection point using an optical waveguide as a standard optical fibre. Optical transport is immune from electromagnetic (EM) interference and allows the signal to reach longer distances compared to electrical cables/PCB traces. This aspect can enable new system architectures that are not constrained by the signal integrity degradation on long electric lines. Additionally, it is possible to apply optical amplification along the path without causing additional noise to the final optical signal.

These advantages are significant for radio transmission systems operating at frequencies of the order of 100GHz and beyond. These systems are affected by signal integrity issues where electrical transmission at lower frequencies allows to transmit over longer distances but increase the phase noise generated at conversion from the low-frequency reference clock to the final clock frequency.

Further, due to the improved signal integrity and intrinsic low noise, embodiments provide a reduction of the complexity at the receiver reducing the need for complex PLLs and equalization circuits with high-speed logics.

Embodiments are also advantageous in terms of footprint of the RF generator since the harmonics that generate the beat signal are selected in the optical domain via cascaded interferometers. It is therefore not necessary to use an electric filter. The space occupied by the interferometers is generally of the order of some hundred micrometers squared, and this value decreases when the frequency of the RF signal to be generated increases. Moreover, the optical signal that carries the harmonics may be split to feed multiple RF integrated circuits (RFIC); in this scenario, performing the selection of the beat signal optically at the photonic chip, avoids the need of electric filters at each RFIC.

The choice of cascaded series of interferometers for the selection of the two harmonics is also advantageous compared with other types of optical filter-based approaches such as micro-ring resonators (MRR) or distributed feedback Bragg reflectors (DFBR). Cascaded interferometers improve flexibility of the design and reduce complexity of the realization and tuning procedure. Optical filters based on DFBR can select a single wavelength at a time. Therefore, this choice would require splitting the optical signal into two branches with a filter for each of the two harmonics and recombine the paths before the output. Using cascaded interferometers in the same branch this constraint is avoided, resulting in a more flexible choice of the design.

On the other hand, filters based on MMR can select more than one frequency, spaced by the free spectral range (FSR) of the ring. Nevertheless, a spacing of the order of 100GHz would require a very sharp profile that is obtained with a large number of coupled rings with tight fabrication tolerances and well-controlled tuning of each ring. This increases the complexity of the fabrication process. Additionally, the number of tuning elements that have to be controlled simultaneously is larger compared to the choice of cascaded interferometers, resulting in an increased complexity of the tuning procedure.

In embodiments. the selection of the comb lines has lower losses and power consumption with respect to alternative implementations that may instead exploit two separated optical carriers (from two different lasers or from the split of the same laser source), each carrying a single harmonic that has been selected from the comb by narrow filtering. Additionally, since the spectral components used for the beat signal travel the same path, there are no issues with possible phase impairments.

Simulation of embodiments demonstrate that the optical carrier does not add any additional noise to the electrical oscillator. Indeed, as the optical signal travels a single path through the filter stages, the optical phase noise introduced by the laser on both selected harmonics is fully correlated, and it is ultimately cancelled after the photodetection of the harmonics' beat signal.

Embodiments exploit the coherence of the optical carrier to cancel the optical phase noise in the heterodyning process of two harmonics of an optical comb, including noise from optical amplification of the signal before photodetection, so that it is possible to obtain a multiplication of the reference frequency without noise addition and no substantial feedback control. Further, the selection of the optical harmonics avoids the use of electrical filters after photodetection, resulting in a smaller footprint and lower production cost.

Modifications and other variants of the described embodiment(s) will come to mind to one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is understood that the embodiment(s) is/are not limited to the specific examples disclosed and that modifications and other variants are intended to be included within the scope of this disclosure. Although specific terms may be employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

It should be noted that the above-mentioned examples illustrate rather than limit the invention, and that those skilled in the art will be able to design many alternative examples without departing from the scope of the appended statements. The word "comprising" does not exclude the presence of elements or steps other than those listed in a claim, "a" or "an" does not exclude a plurality, and a single processor or other unit may fulfil the functions of several units recited in the statements below. Where the terms, "first", "second" etc. are used they are to be understood merely as labels for the convenient identification of a particular feature. In particular, they are not to be interpreted as describing the first or the second feature of a plurality of such features (i.e. the first or second of such features to occur in time or space) unless explicitly stated otherwise. Steps in the methods disclosed herein may be carried out in any order unless expressly otherwise stated. Any reference signs in the statements shall not be construed to limit their scope.

CLAIMS

1. A radio frequency signal generator comprising:

an optical comb generator module arranged to provide a plurality of spectral components at spaced wavelengths;

an optical filter module coupled to the optical comb generator module and an optical-to-electrical converter device;

the optical filter module comprising a plurality of interferometer devices coupled in series, each interferometer device arranged to remove a respective set of spectral components from the plurality of spectral components in order to output predetermined spectral components from the optical filter module to the optical-to-electrical converter device, the predetermined spectral components being a subset of the plurality of spectral components;

the optical-to-electrical converter device arranged to heterodyne the predetermined spectral components to generate a radio frequency signal.

2. The radio frequency signal generator of claim 1, wherein each interferometer device has two branches arranged to cause different optical propagation delays to spectral components passing therethrough in order to remove some spectral components using destructive interference, wherein the difference in optical propagation delays between the two branches of respective interferometer devices is different in order to remove different sets of spectral components.

3. The radio frequency signal generator according to claim 1 or 2, wherein a said interferometer device comprises a coupler having an input port coupled to the optical comb generator module and two output ports coupled to respective branches, a combiner having two input ports each coupled to a respective branch and an output port configured to select an interference field of optical radiation from the two branches.

4. The radio frequency signal generator of claim 3, wherein the coupler and/or the combiner comprise one of the following: a directional coupler; a multimode interferometer.

5. The radio frequency signal generator of claim 3 or 4, wherein the combiner comprises a second output port configured to select an interference field of optical radiation from the two branches which is complimentary to the first interference field of the first output port.

6 The radio frequency signal generator of any one of claims 3 to 5, wherein the optical

filter module comprises one or more interferometer devices having an input coupled to a said port of a preceding interferometer device.

7. The generator of any one preceding claim, wherein a said interferometer device is arranged to double the spacing between the spectral components output from said interferometer device compared with the spectral components input into said interferometer device.

8. The generator according to any one preceding claim, wherein the optical comb generator comprises a phase modulator arranged to modulate an input optical signal with a modulating signal to provide the plurality of spectral components as harmonics of the modulating signal.

9. The generator according to claim 8, wherein the optical comb generator comprises a continuous wave laser coupled to the phase modulator.

10. The generator according to claim 8 or 9, wherein the different optical propagation delays between the branches of each interferometer device is a fraction of the period of the modulating signal.

11. The generator according to claim 8, wherein the interferometer devices in the optical filter module have the following sequence of differences in propagation optical propagation delay between branches as a proportion of the period of the modulating signal: 0.5; 0.25; 0.125.

12. The generator according to any one preceding claim, wherein a said branch of a said interferometer device is associated with a control element arranged to change the refractive index of said branch in order to change the optical propagation delay therethrough.

13. The generator according to any one preceding claim, wherein the interferometer devices are unbalanced Mach-Zehnder Interferometers.

14. A method of generating a radio frequency signal, the method comprising:

generating a plurality of spectral components at spaced wavelengths by acting on an optical input signal;

filtering the plurality of spectral components using a series of interferometer devices arranged to remove respective sets of spectral components in order to output predetermined spectral components;

heterodyning the predetermined spectral components in order to generate the radio frequency signal.

15. The method of claim 14, wherein the heterodyning uses an optical-to-electrical conversion device.

16. The method of claim 14 or 15, wherein each interferometer device causes different optical propagation delays to spectral components passing therethrough such that destructive interference removes some spectral components, wherein the difference in optical propagation delays between the two branches of respective interferometer devices is different in order to remove different sets of spectral components.

17. The method of any one of claims 14 to 16, wherein the plurality of spectral components at spaced wavelengths are harmonics of a modulating signal acting on the optical signal.

18. The method of claim 17, comprising controlling the wavelength of the radio frequency signal by adjusting the wavelength of the modulating signal.

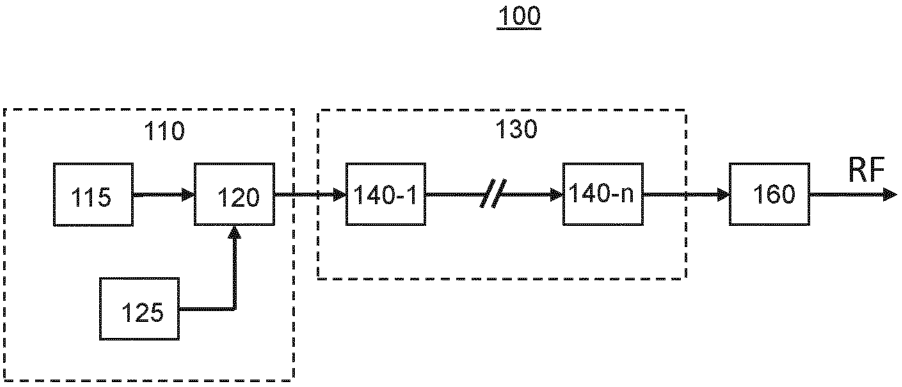


Figure 1

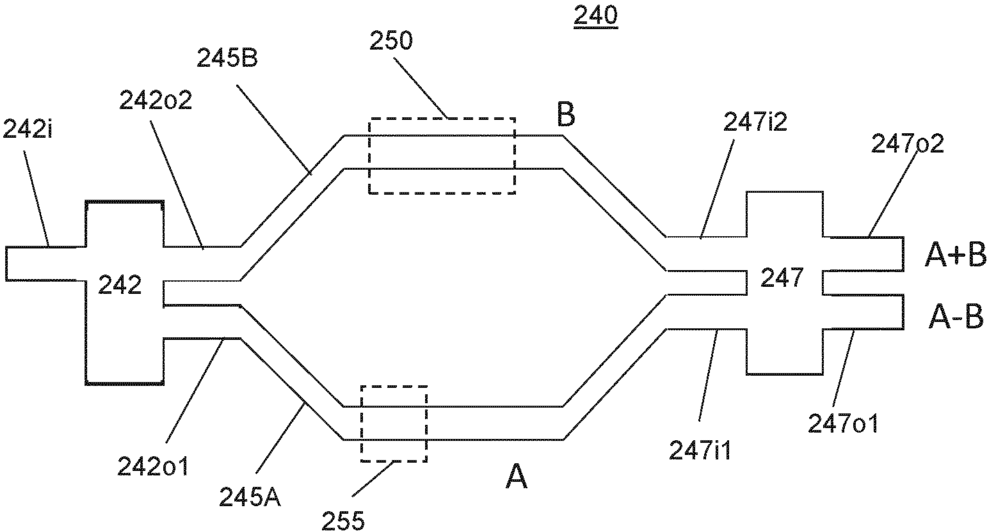
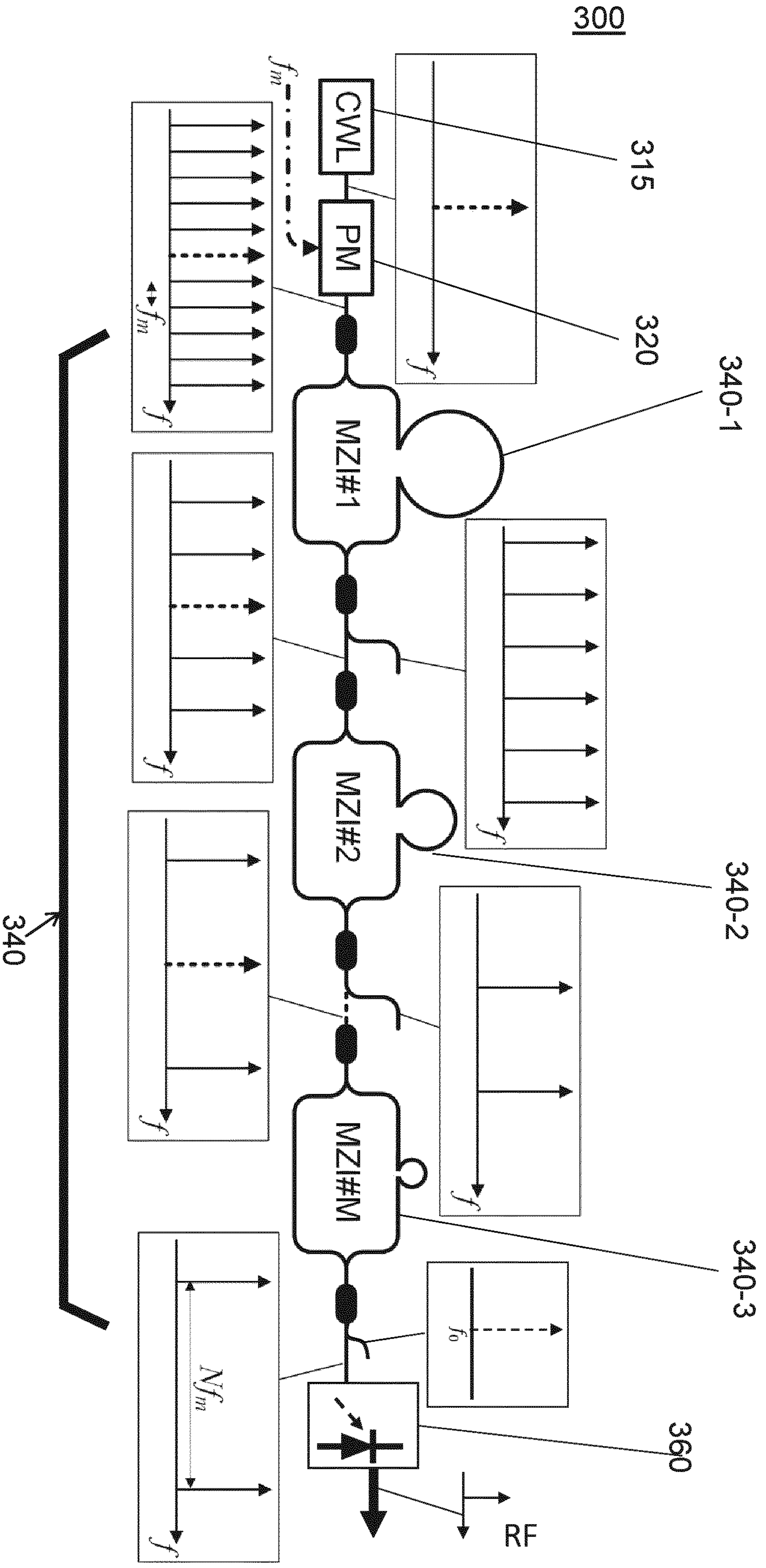


Figure 2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CWL
PM
MZI#1
MZI#2
MZI#M
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340-2
340-3
340
360
RF
f_m
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Figure 3

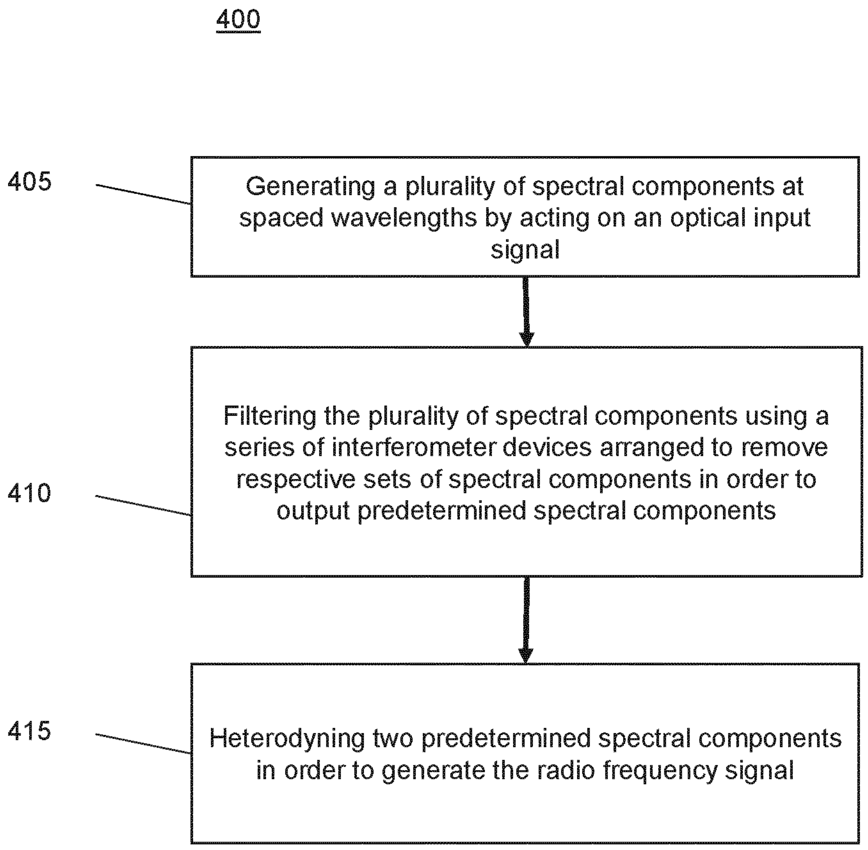


Figure 4

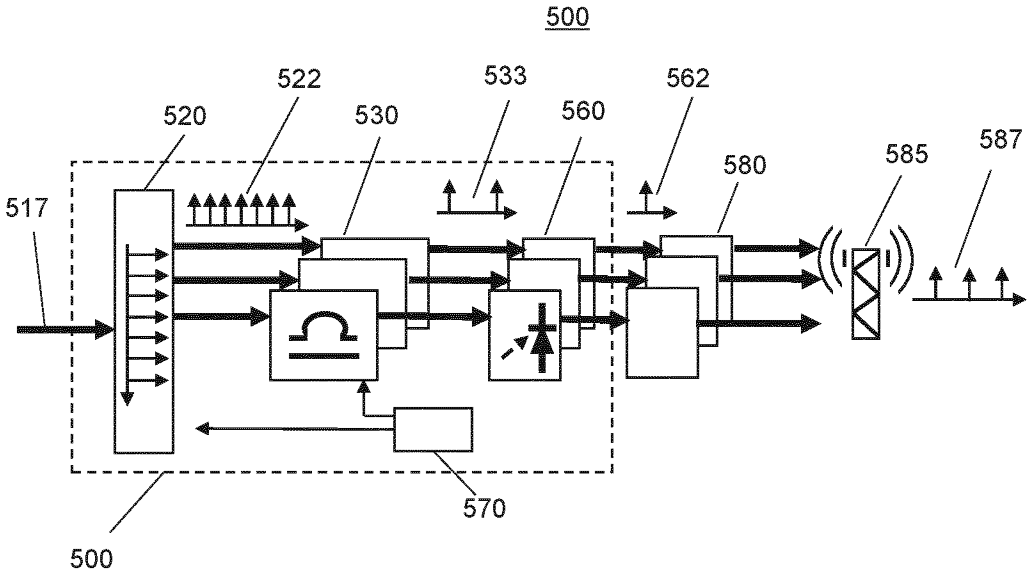


Figure 5

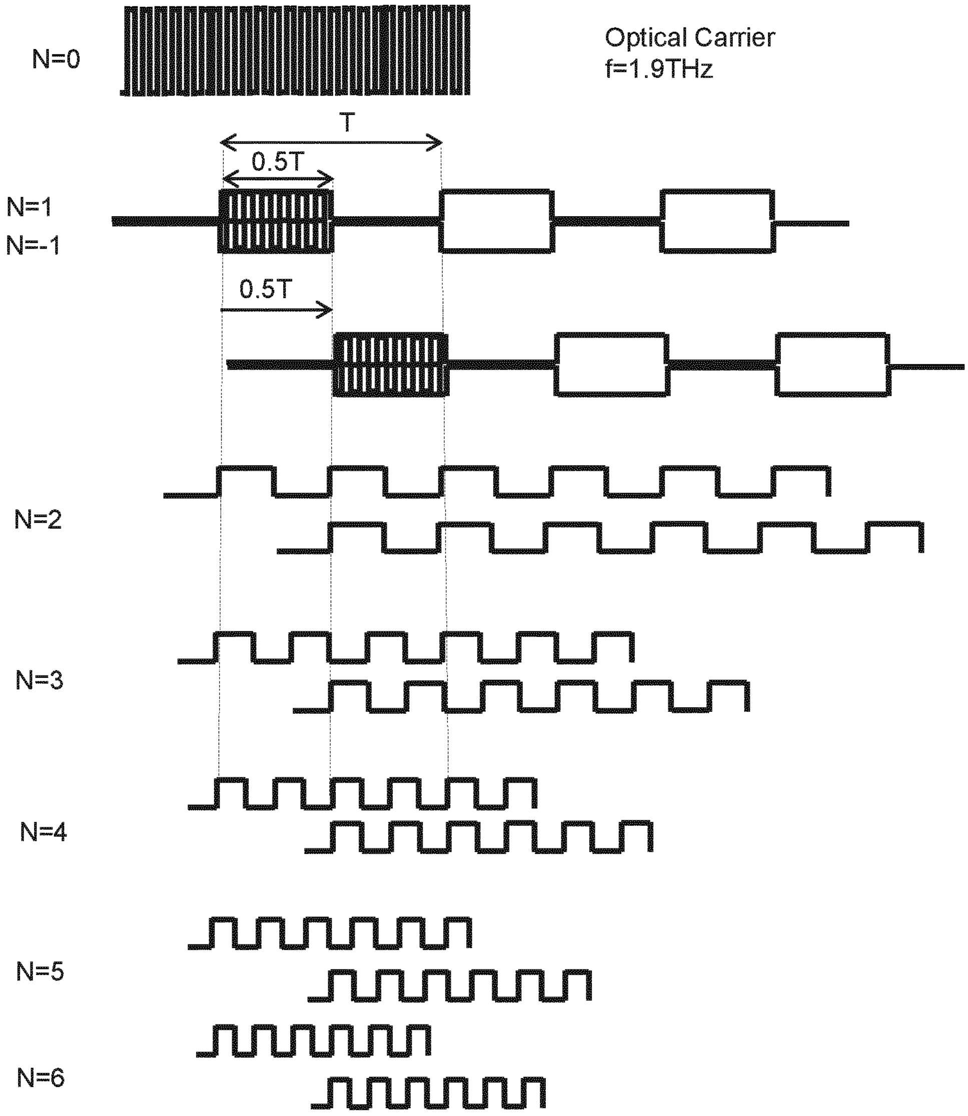


Figure 6A

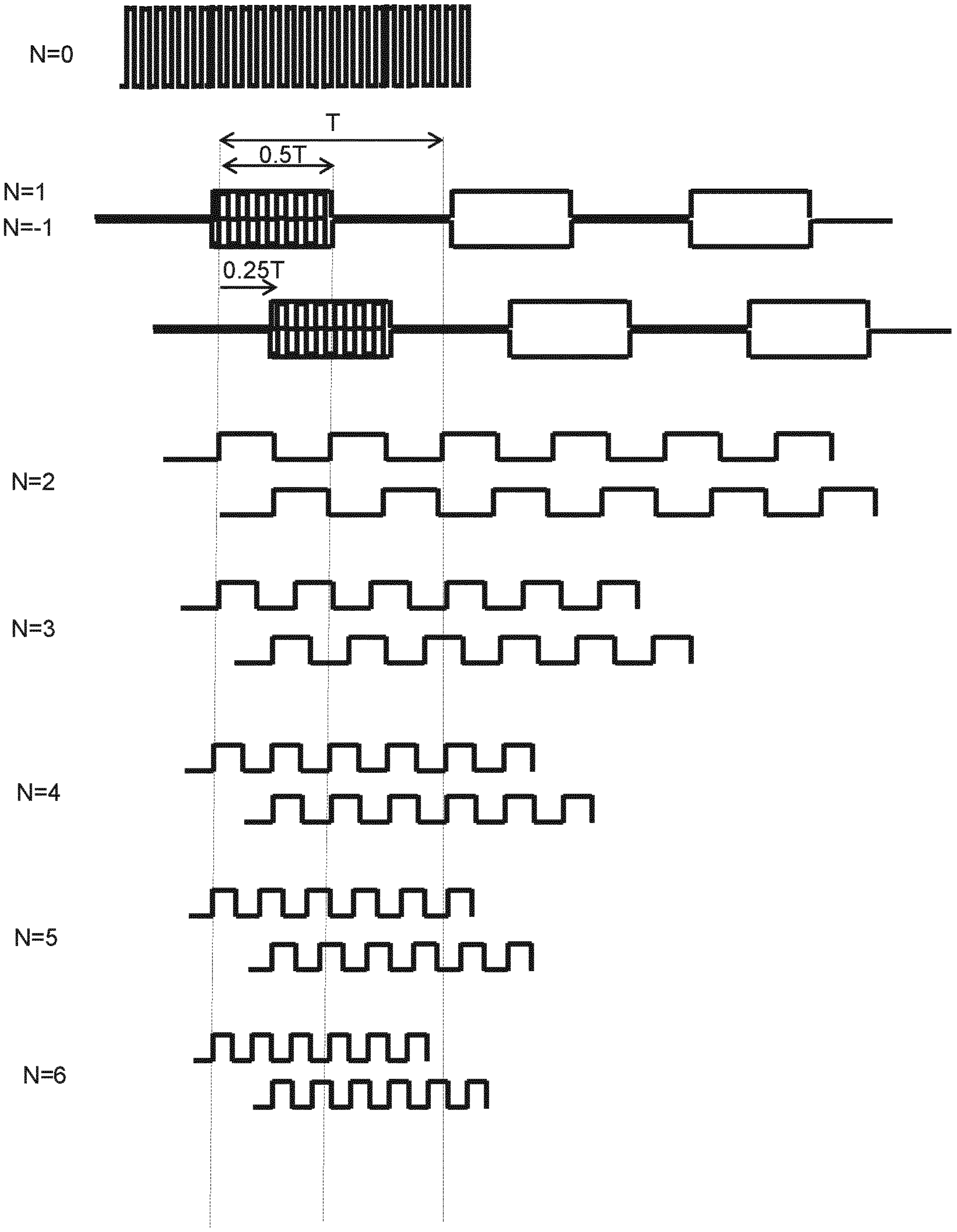


Figure 6B

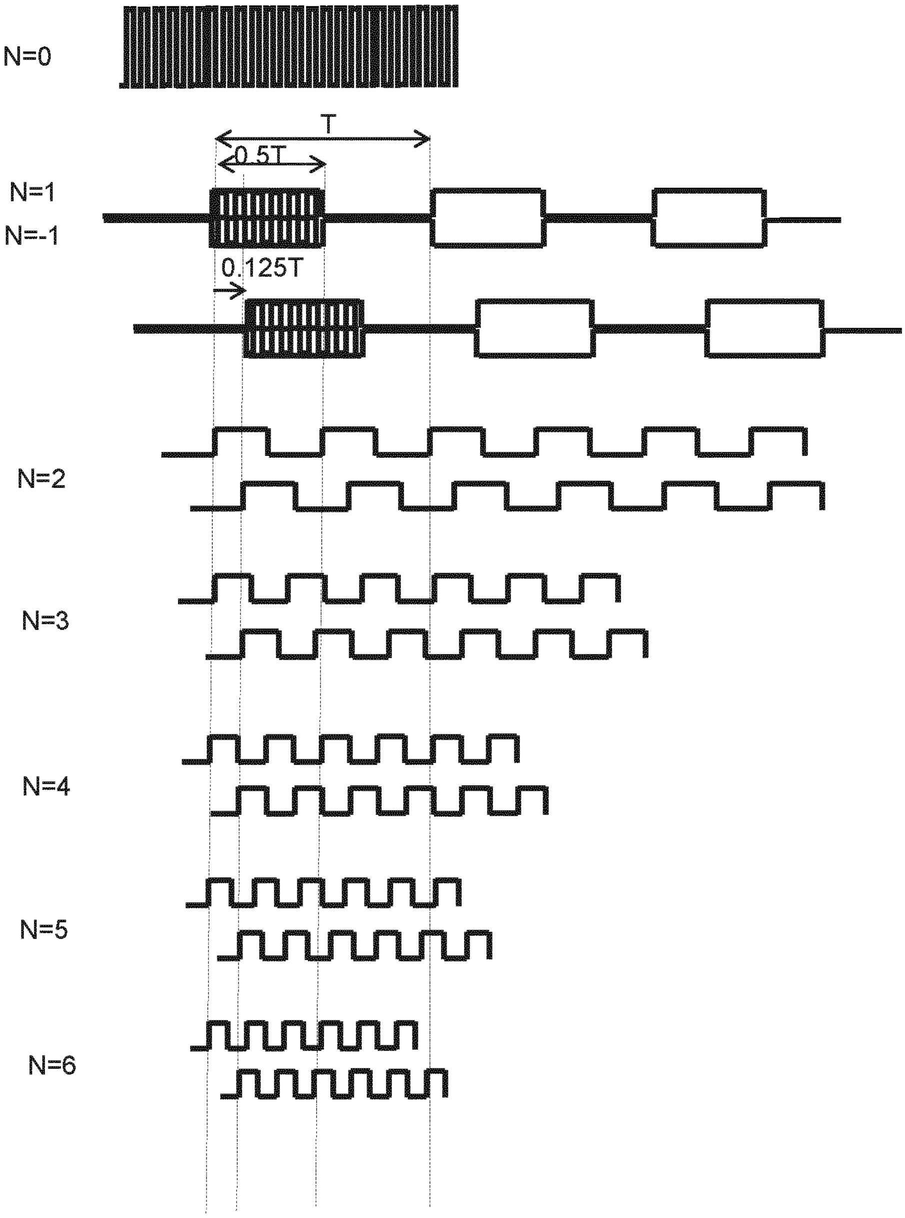
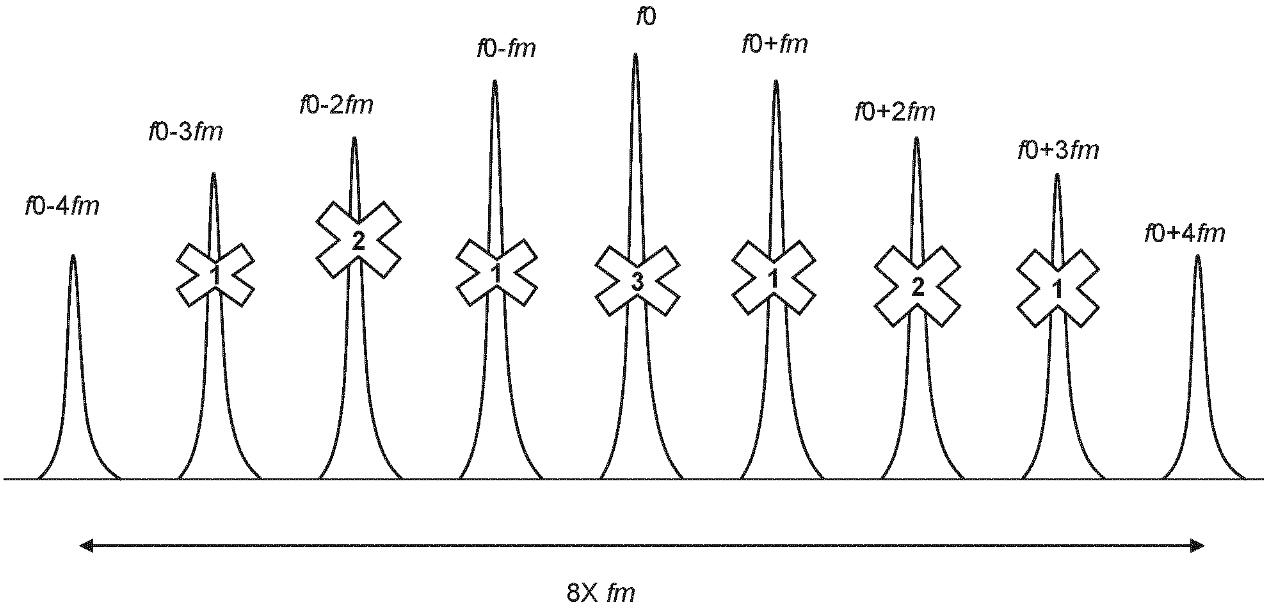


Figure 6C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f0-3fm
f0-2fm
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1
2
1
3
1
2
1
8X fm

Figure 7

INTERNATIONAL SEARCH REPORT

International application No

PCT/EP2021/059116

A. CLASSIFICATION OF SUBJECT MATTER

INV. H04B10/2575 G02B6/12 G02F1/21 G02F1/225 H04J14/02

ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

H04B G02B G02F H04J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Y	US 2018/054175 A1 (FOK MABLE P [US] ET AL) 22 February 2018 (2018-02-22) figures 8A, 9A-9H paragraphs [0038] - [0042] -----	1-18
Y	MONTASIR QASYMEH ET AL: "Frequency-Tunable Microwave Generation Based on Time-Delayed Optical Combs", IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, IEEE, USA, vol. 59, no. 11, 1 November 2011 (2011-11-01), pages 2987-2993, XP011374624, ISSN: 0018-9480, DOI: 10.1109/TMTT.2011.2165963 figure 1 II. PRINCIPLE -----	1,14

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☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search 21 December 2021	Date of mailing of the international search report 07/01/2022
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Lobato Polo, I

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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2021/059116

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WILLNER ALAN E ET AL: "Optical Signal Processing Aided by Optical Frequency Combs", IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, IEEE, USA, vol. 27, no. 2, 22 October 2020 (2020-10-22), pages 1-16, XP011818896, ISSN: 1077-260X, DOI: 10.1109/JSTQE.2020.3032554 [retrieved on 2020-11-05] figure 5 C. Optical Frequency Combs -----	1-18
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A	US 2010/104277 A1 (ROBINSON BRYAN S [US] ET AL) 29 April 2010 (2010-04-29) figure 6 paragraphs [0039] - [0045] -----	1-18
A	US 2003/053747 A1 (CORMACK ROBERT H [US]) 20 March 2003 (2003-03-20) the whole document -----	1-18

3

Form PCT/ISA/210 (continuation of second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

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			US	2013148983	A1	13-06-2013
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