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(54) **Optical delay element**

(57) A delay element for delaying an input signal (110) having a frequency spectrum into an output signal (150) representing the input signal delayed in time comprises a filter unit (120) for splitting the input signal (110) into at least two filter signals to the frequency spectrum

of the input signal (110), and a modulation unit (130) for modulating at least one of the filter signals. A combining unit (140) is provided for combining the at least one modulated filter signal and any non-modulated filter signal into the output signal (150).

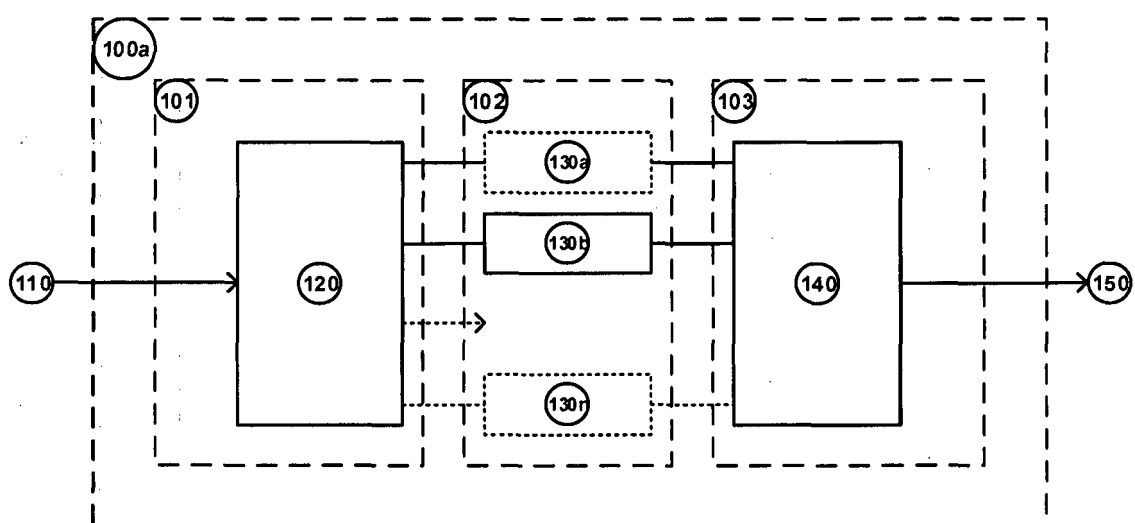


FIG. 6

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DescriptionTechnical Field

5 **[0001]** The invention is related to a delay element and to a method for delaying an input signal.

Background Art

10 **[0002]** Delay elements are required for many applications, and especially tunable delay elements are desired in many technical fields.

Disclosure of the Invention

15 **[0003]** According to an aspect of the present invention, a delay element comprises a filter unit for splitting an input signal into two or more signals referred to as filter signals. One or more of the filter signals are then modulated in a modulation unit, and preferably are offset by a phase or a complex amplitude therein, before they are recombined in a combination unit into a single signal which is the output signal. Hence, the combination unit recombines the modulated one or more filter signals and the one or more non-modulated filter signals into the output signal which represents the delayed input signal.

20 **[0004]** In a preferred embodiment, the filter unit splits the input signal with a frequency dependent splitting ratio or phase ratio. In a preferred embodiment, each filter signal is derived from the input signal by applying a filter characteristic that changes over frequency, e.g. linear, or sinusoidal.

25 **[0005]** In a preferred embodiment, the filter unit splits the input signal in such a way, that the filter signals complement to a frequency spectrum of the input signal. In this embodiment, the filter signals provided by the filter unit may therefore be also referred to as filter signals.

[0006] In a preferred embodiment, the parameter of the at least one filter signal to be modulated is one or more a phase, an amplitude, a frequency, a polarization. Preferably, the parameter to be modulated is tunable in its magnitude.

30 **[0007]** In an embodiment of the present invention, a phase of the at least one filter signal is modulated while its amplitude preferably is maintained constant. The phase modulation is responsible for the time delay in the output signal. Preferably, a phase shift to be applied to the at least one filter signal is adjustable. This characteristic makes the delay element be tunable in time.

[0008] In another embodiment of the present invention, an amplitude of the at least one filter signal is modulated while its phase preferably is maintained constant. Here, the amplitude modulation is responsible for the time delay in the output signal. Preferably, the amplitude is adjustable. This characteristic makes the delay element be tunable in time.

35 **[0009]** In a preferred embodiment of the present invention, the modulation unit is configured to modulate a phase of exactly one of the filter signals. In this context, it is preferred that the filter unit splits the input signal into exactly two filter signals. In the following, the modulation unit preferably acts on only one of the filter signals while the other filter signal remains unaffected in phase. In this concept, the filter signal to be modulated preferably is phase-shifted by $-\pi/2 < \varphi < \pi/2$.

40 **[0010]** This phase shift invokes, after a recombination of the modulated filter signal and the non-modulated filter signal a resulting output signal that represents the input signal delayed in time. In this particular embodiment, the delay element requires only one filter unit, one phase modulator in the modulation unit and one coupler in the combination unit and as such allows for an implementation with few elements only.

45 **[0011]** The filter unit can comprise any type of filter or filters depending on a desired frequency response of the delay element. The shape and types of the one or more individual filters of the filter unit may have a frequency response which is linear or nonlinear with the frequency, and in case of multiple filters provided these filters may be cascaded, i.e. sequentially arranged, or come as a combination of parallel filters, e.g. in order to optimize a frequency response of the overall filter unit.

50 **[0012]** In an embodiment, the filter unit may preferably comprise a spatial light modulator - such as a Waveshaper™ from Finisar™ (trademarks of Finisar or another third party) - providing a very flexible all-purpose implementation which can be tuned to form any possible filter characteristic. In other embodiments the filter could e.g. comprise of a delay interferometer, a Fabry-Perot Etalon filter, a thin film filter, a Bragg-Grating filter, a prism filter, an arrayed waveguide grating router filter, etc., which all have a frequency dependent response when tuned to the edge of the passband. Any of these filters can be implemented in different ways. E.g. the delay interferometer can be implemented as a free space delay interferometer, as a fiber interferometer, as an integrated optic interferometer, as a birefringent material interferometer in a fiber, a crystal, etc. Many other implementations can be considered for those skilled in the art.

55 **[0013]** In one embodiment, the modulation unit comprises one or more optical modulators, and in particular one or more phase-shifter elements based on a linear electro-optic effect. Such elements typically offer an ultra-fast phase tuning, i.e. a ultra-fast response / low settling time to a tuning of the phase as small as 0.1 ns given a tunability of the

modulation unit of e.g. 10 GHz. As a result, the tunable time delay element as such is tunable ultra-fast as well. In other embodiments the modulation unit can be based on the Kerr-effect, the quantum confined Stark effect, the plasma dispersion effect, the Franz-Keldysh effect, cross-phase or cross-gain modulation effects, nematic liquid or thermal effects or many other physical effects. A modulator of the modulation unit can be arranged as a single unit phase-modulator or arranged in a Mach-Zehnder or Michelson Interferometer or ring filter configurations. Again, many configurations can be used to modulate the phase or magnitude of a signal. If the filter signal that is fed into the modulation unit is an electrical signal the modulator preferably is based on a mechanical delay element.

[0014] The combination unit can comprise an electrical or an optical coupler, or any other means for summing up signals, in particular by interference effects.

[0015] Advantageously, a concept for a preferably continuously tunable and a preferably ultra-fast continuously tunable time delay is introduced that can be used for both RF and optical applications or applications that rely on a combination of both. In an embodiment where the modulation unit affects the phase of one or more of the filter signals, the delay element may also be referred to as complementary phase shifted spectrum delay element. In a preferred embodiment, the input signal and the output signal are one of an electrical signal, and in particular a radio-frequency signal, and an optical signal. Embodiments of the present delay elements offer tunability as to the delay time, an ultra-fast settling time and a large bandwidth at the same time. This offers a wide range of new applications where a fast switching between different modulation parameters, e.g. resulting in a fast switching between different delay times, is crucial. The switching time may be defined as a settling time to change from one phase shift to another phase shift resulting in the case of phase modulation, for example.

[0016] In a preferred embodiment, a delay element according to an embodiment of the present invention may be used in a phase array feeder, and especially in a beam array feeder, e.g. employable in next generation wireless networks and allowing new utilizations owed to an ultra-fast tunability of steering directions, and / or an ultra-fast beam stabilization for long range communication and / or a space-time division multiplexing. In the case of the long range stabilization, such a system would have the ability to overcome the effect of the atmosphere on the transmission channel allowing a longer transmission distance, a faster speed and / or an advanced modulation format.

[0017] A -delay element according to an embodiment of the present invention may also be employed in a tunable filter for communications, or for the generation of flexible modulation formats such as e.g. pulse position modulation, space division multiplexing etc.

[0018] Other exemplary implementations may be in radar or sensing, in radio-frequency and optical signal processing, in multiplexing/de-multiplexing signals, etc.

[0019] In a particular case of a clock recovery system, the delay element according to an embodiment of the present invention allows an all-optical system with ultra-fast stabilization of the input signal. Such an implementation would therefore provide real time synchronization without digital signal processing.

[0020] In a preferred embodiment, the delay element comprises one or more or all units implemented in either an optical free space technology in which optical signals are transmitted in free space, or as bulk components comprising of waveguides and / or fibers (RF waveguides, optical fibers, etc.), or in an integrated technology.

[0021] Preferably, the individual units of the delay element may be implemented by cascades, i.e. sequentially arranged filters, modulators, etc. for achieving an optimized frequency response for generating a true time delay element.

[0022] In another embodiment, the delay element is generated by using an optical interference technique. Such an interferometer system may also be implemented as a photonic integrated circuit (PIC) using ring resonators, a delay line or any other component able to generate the requested filter unit in an integrated system. A similar system could be based on free space optic.

[0023] In the embodiment comprising an interferometer, it is preferred that the two filter signals propagate in the same single waveguide or fiber and have different polarizations, i.e. polarization multiplexing is applied to remove phase noise. A polarization maintaining fiber may be comprised in the filter unit to generate an interferometer delay. Then, a polarization dependent modulator may be comprised in the modulation unit to apply a phase shift on only one of the complementary spectrums.

[0024] In another embodiment of the present invention, a reference signal is provided which may be used as an up or down-conversion of the input signal with respect to frequency. Hence, the reference signal is frequency offset compared to the input signal. The reference signal may in a preferred embodiment be shifted in phase. Preferably, the reference signal is an optical signal, and in particular a laser signal such that the phase shift may delay a baseband signal and a carrier of the reference signal. The phase shift may be applied at any point using de-multiplexing if requested, and in particular may be applied after the mixing of the two signals. In a preferred embodiment a control for the modulation of the filter signal and the reference signal may be coupled such that both modulators may be driven by the same control signal. This can be achieved either by applying modulators with different properties, such as different length, doping, structure, in order to have different effects in response to the same control signal, or by adding introducing an amplifier with a gain corresponding to a requested difference in length between the modulators.

[0025] In the case of applications where the delay range has to be enhanced, multiple instances of the present

embodiments may be cascaded. Even more than two complementary signals may be used.

[0026] It is preferred that the present delay element may be embodied in one or more of a phased array feeder, a clock recovery system, or a multiplexer. When applied in a phase array feeder for processing signals to be supplied to an array of n antennas, the phase array feeder comprises a delay element according to any one of the embodiments for supplying the output signal of which delay element to one of the n antennas of the array. In addition, $n-1$ additional modulation units and $n-1$ additional combination units are provided. A splitter is provided to distribute the filter signals supplied by the filter unit to all of the additional modulation units, too. In this context, the present embodiment virtually provides n delay elements while these delay elements share a common filter unit. The splitter may in a more general sense be regarded as a unit for supplying the filter signals provided by the filter unit to each of the additional modulation units. This unit may be considered as a power divider to generate as many copies of the input signal as requested for the given array size.

[0027] Each modulation unit then modulates at least one of the filter signals supplied thereto. Preferably, all the modulation units are configured to modulate by a different phase offset. Each additional combining unit is configured to combine at least one modulated filter signal of the assigned additional modulation unit and any filter signal not modulated by the assigned additional modulation unit into a corresponding output signal to be supplied to an associate antenna of array. Each additional modulation unit may comprise a phase modulator for driving both the filter signal phase modulation and an offset phase modulation applied to a reference signal if any. The phase modulator may be implemented in parallel, in series or a combination of both. Preferably, an azimuth and an elevation angle in the phase are driven by two different control signals. This can be achieved by cascading two individual phase modulators in the modulation unit, one of which is responsible for applying an azimuth phase offset, the other one being responsible for applying an elevation phase offset to the filter signal. However, in case of a separate modulator for azimuth and elevation angle for the filter signal in combination with a separate modulator for azimuth and elevation angle for the reference signal, it may be preferred that an effective ratio between the azimuth angles as well as between the elevation angles is constant each, which in one embodiment may be implemented by a coupling of the control signals for the corresponding two phase modulators.

[0028] In a preferred embodiment, the filter unit, the modulation unit, and the combining unit are integrated on a common substrate.

[0029] According to another aspect of the present invention, a method is provided for delaying an input signal having a frequency spectrum. The input signal is split into at least two signals filter to the frequency spectrum of the input signal. At least one of the filter signals is modulated, and at least one modulated filter signal and any non-modulated filter signal are combined into an output signal representing the input signal delayed in time.

[0030] Hence, a frequency response of the delay element is generated by means of an interference effect between complementary signal spectra at least one of which is tunable by means of a modulation unit acting on one of magnitude, phase, polarization or frequency.

[0031] In a preferred embodiment, the delay element may be operated sequentially, i.e. it may process several input signals at different frequencies consecutively. In another embodiment, several input signals at different frequencies may be processed at the same time.

[0032] The described embodiments similarly pertain to the method, and the delay element. Synergetic effects may arise from different combinations of the embodiments although they might not be described in detail.

[0033] Other advantageous embodiments are listed in the dependent claims as well as in the description below.

Brief Description of the Drawings

[0034] The embodiments defined above and further embodiments, features and advantages of the present invention can also be derived from the examples to be described hereinafter and are explained with reference to the annexed drawings, wherein:

Figure 1 illustrates in a block diagram a transformation of an input signal into an output signal in the frequency domain and in the complex domain by an ideal delay element,

Figure 2 illustrates a magnitude and a phase response of a delay element according to Figure 1,

Figure 3 and Figure 4 each depict at least parts of a delay element for delaying an input signal in time according to an embodiment of the present invention,

Figure 5 illustrates a magnitude and a phase response of the tunable time delay element of Figure 3 or Figure 4,

Figure 6 illustrates a block diagram of a delay element according to an embodiment of the present invention,

Figure 7 illustrates a block diagram of a delay element according to another embodiment of the present invention and Figure 8 an according response in magnitude and phase,

Figures 9 to 11 each illustrates a block diagram of a delay element according to an embodiment of the present invention,

Figures 12 illustrates a block diagram of a phase array feeder according to an embodiment of the present invention,

and Figure 13 a corresponding implementation of a part thereof, and Figure 14 illustrates an application of a tunable time delay element according to an embodiment of the present invention.

Detailed Description of Embodiments

[0035] In the general framework of the Fourier theory, a true time delay for an input signal $g(t)$ in the time domain can be translated into the spectral domain by applying a Fourier transform (FT)

$$FT[g(t - \Delta t)] = e^{-i2\pi\Delta t \cdot f} \cdot \hat{g}(f) \quad 1)$$

where Δt is the time delay, $g(t)$ is an unknown function g in time domain t , also referred to as input signal, and $\hat{g}(f)$ is the Fourier transform in the frequency domain f corresponding to $g(t)$, also referred to as output signal. Hence, in order to generate a time delay Δt , a frequency response of a time delay element implementing the time delay Δt has the form of

$$H_{TTD}(f) = e^{-i2\pi\Delta t \cdot f} \quad 2)$$

[0036] This frequency response can be understood as a phase shift that changes linearly with the frequency f .

[0037] Figure 1 depicts the effect of a perfect delay element onto a signal. An input signal Sig_{in} in diagram L, exemplary chosen as Nyquist signal, is depicted using a magnitude (absolute value of the complex amplitude) and phase versus frequency representation and using a complex domain representation. After an ideal delay element FI, an output signal Sig_{out} exhibits the characteristic depicted in diagram M. Using the input signal Sig_{in} as reference the effect of a delay element is thus, in the frequency representation, a linear phase versus frequency and no changes on the amplitude. In the complex domain representation, this corresponds to different angles for the different phasors while their lengths stay constant.

[0038] Figure 2 depicts in diagram a) a magnitude and in diagram b) a phase response over frequency f of an ideal time delay element for different delay times Δt . Any device aiming to act as a tunable time delay element needs therefore a similar set of frequency responses. Figure 3 depicts a delay element according to an embodiment of the invention. The tunable time delay element comprises: A first section 101 with a filter unit 120 generating two signals B and C filter to an input signal 110 depicted in A, that is supplied to the filter unit 120 A second section 102 where one or more of the filter signals B and C - and in the present example only the filter signal C - are modulated by a modulation unit 130 by an exemplary phase, to form modulated filter signals, and in the present embodiment one modulated filter signal E and another non-modulated filter signal D. In a third section 103, the modulated filter signal E is combined with the non-modulated filter signal D by a combining unit 140 to generate by superposition an output signal 150 depicted in F. Due to a frequency depending splitting ratio of the input signal 110 in the filter unit 120 including the generation of complementary signals B and C, the superposition after phase modulation will exhibit a phase shift that changes with frequency. This effect can be better understood by looking at the complex domain representation of the signals D, E and F. In the non-modulated filter signal D, the phasors can be considered having an angle of zero as they are used as reference. In the modulated filter signal E, the phasors are at an angle or phase corresponding to the applied phase shift in the modulation unit 130, here exemplary of $\pi/2$. Using the complex addition theorem, the output signal 150 according to F is a vectorial sum of the different frequency components from both signals D and E. As depicted in F, the resulting phasors of the output signal 150 have different angles for different frequencies as an amplitude ratio of the filter signals B and C are not constant. In the amplitude and phase versus frequency representation, the output signal 150 in F exhibits therefore a similar characteristic as with the theoretical time delay element depicted in Figure 1 such that this embodiment can be considered as an approximation of a true time delay element.

[0039] Figure 4 illustrates a part of the delay element of Figure 3 to demonstrate the tunable nature of the delay element of Figure 3. In the modulation unit 130, the modulator now applies a phase shift of $n/4$ instead of $n/2$ to form the modulated filter signal E while the non-modulated filter signal D is not changed compared to Figure 3. The result of the complex addition in the combining unit 140 exhibits thereby a different relation leading to a different phase versus frequency i.e. another time delay. The phase modulator is thus acting as a tunable element to generate different time delays and can be tuned between $-n/2 < 0 < n/2$ without strong signal deterioration.

[0040] Figure 5 depicts a set of frequency responses with different applied phase shifts. The complementary spectrums in this example are plotted for the filter units of Figure 3 and 4, i.e. they correspond to triangular spectrums.

[0041] The frequency response depicted in Figure 5 may mathematically be computed using the following principles exemplarily applied to the embodiments of Figure 3 and 4. First, the frequency response H_{CPSS} of the tunable time delay element of Figure 3 or Figure 4 is

$$H_{CPSS} = H_{f1} + H_{\alpha} \cdot H_{f2} \quad (3)$$

where H_{f1} and H_{f2} are frequency responses of two output ports of the filter unit 120 and H_{α} is a frequency response of the respective modulation unit 130. In this exemplary implementation the frequency dependent responses are

$$H_{f1}(f) = 1 - \frac{f}{B}; \quad H_{f2}(f) = \frac{f}{B}; \quad H_{\alpha} = e^{i\alpha} \quad (4)$$

where B is the bandwidth of the incoming signal, f the frequency (f takes values between 0 and B) and α is the phase offset induced onto the second complementary signal C. Inserting (4) in ((3)), the frequency response depicted in Figure 5 is

$$H_{CPSS}(f) = 1 - \frac{f}{B} + \frac{f}{B} \cdot e^{i\alpha} \quad (5)$$

[0042] The frequency response of a tunable time delay element according to any embodiment of the present invention at least depends on the type of filter used in the filter unit for splitting the input signal into the two or more complementary signals. A filter unit generating complementary signals may preferably have the following characteristics: the resulting filter signals share the same bandwidth and their amplitudes correspond to a frequency dependent splitting ratio of the input signal. The frequency dependent splitting ratio depicted in for the filter units 120 of Figures 3 and 4 is exemplarily generating a triangle spectrum but any other shapes to optimize the frequency responses of the tunable time delay element would work according to the same principle.

[0043] Figure 6 illustrates a block diagram 100a of a tunable time delay element according to an embodiment of the present invention. An input signal 110 is split in a first section 101 by a filter unit 120 into two or more filter signals, the set of filter signals complement to the frequency spectrum of the input signal 110. Hence, a frequency dependent splitting ratio is applied in the filter unit 120 across the signal spectrum. One or more of the filter signals supplied at output ports of the filter unit 120 are then offset by phase or complex amplitude by modulators in combination representing a modulation unit 130 - although in the present and other embodiments the individual modulators are referred to by 130 - in a second section 102 before they are recombined into a single output signal 150 in a combination unit 140 of a third section 103.

[0044] Figure 7 illustrates a block diagram of a tunable time delay element according to another embodiment of the present invention. Here, the filter unit 120 comprises an interferometer such as one of a Mach-Zehnder, a delay-interferometer, a Michelson, a ring filter etc. for generating two filter signals from the input signal. In a different embodiment, the filter unit 120 may contain a WDM de-multiplexer or any filter leading to sinusoidal magnitude frequency responses. In case of an interferometer a free spectral range (FSR) preferably is chosen to be about twice the bandwidth of the input signal 110 in order to improve the working range and the tuning of the time delay.

[0045] Compared to the embodiment of Figure 3, in the present embodiment the outputs of the interferometer 121, i.e. the filter signals are cosine and sinusoidal functions in frequency instead of being linear in frequency, but similar frequency responses occur as shown for the previous embodiment. The frequency responses of the filters 121 generating the filter signals are depicted as 121a and 121b as insets of Figure 7.

[0046] Figure 8 depicts a corresponding frequency response for different phase shifts of a tunable time delay element comprising an interferometer 121 such as shown in Figure 7. While the magnitude is not flat in all the cases, the phase is almost linear in any of the situations. Therefore, this embodiment with the delay interferometer filter represents an ultra-fast tunable time delay element. In an embodiment, the filter units of Figure 6 and / or Figure 7 may be cascaded.

[0047] Figure 9 depicts a block diagram of a tunable time delay element according to another embodiment of the present invention. The present filter unit comprises a fiber based delay interferometer. In a first section 201, an input signal 210 is tuned in a polarization controller 211 to have a 45° polarization before entering a polarization maintaining

fiber 222 leading to a delay of signals at two outputs of the fiber 222 due to fiber birefringence between the slow and fast fiber axis. In another polarization controller 223, the two signals are then again rotated by 45° degrees so that interferences can take place on the vertical and horizontal polarization to generate two filter signals at the filter unit outputs. Hence, in the present example, the filter unit may preferably contain a sequential arrangement of a polarization controller 211, a fiber 222, and another polarization controller 223. Depending on the polarization alignment of the phase modulator a different setup could be used achieving the same functions.

[0048] In a second section 202, the filter signals are then fed into a modulation unit that is embodied as polarization sensitive phase modulator 230 which is configured to allow offsetting the phase in one polarization only. Subsequently, in a last section 203 a combination unit contains a polarization controller 241 in which the signals in the two polarizations, i.e. one filter signal and one phase modulated filter signal, are rotated again in order to generate the desired output signal 250 after the polarizer 242. The output signal 250 could thus be used directly or enter a photodiode.

[0049] Hence, in the present embodiment, all signals are optical signals and the filtering unit, the modulation unit and the combination unit are acting on the various optical signals in a single waveguide used for propagating.

[0050] Generally, and without limitation to the embodiments of Figure 9 or previous embodiments, the interferometer system could also be implemented as a photonic integrated circuit (PIC) using a ring resonator, an optical delay element arrangement, or any other component able to generate the requested filter unit in an integrated system. The modulation unit may be implemented depending on the specific application. In another embodiment, a free space optical unit may be used for implementing the filter unit and / or the modulation unit, such that a free spectral range FSR may be changed easily. Such an embodiment may allow to be used for signals of different bandwidth just by tuning.

[0051] Figure 10 shows a block diagram of a tunable time delay element according to another embodiment of the present invention which in addition allows RF or microwave signal generation by photonics mixing. This embodiment contains as additional feature a down- or up-converter 380, where the signal from the tunable time delay element is combined with a reference signal 360 having a different frequency, i.e. having a frequency difference with respect to the input signal 310. A phase modulator 370 might be needed to adjust the phase of the reference signal 360.

[0052] In a first section 301, an input signal 310 is split into one or more filter signals by means of a filter unit 320. Then one or more filter signals at the outputs of the filter unit 320 are phase shifted in a modulation unit 330 in a second section 302 before being recombined in a coupler 340. In addition, the recombined signal at the output of the coupler 340 - i.e. the signal carrying information- is combined with the reference signal 360 or the phase shifted reference signal in the down- or up-converter 380.

[0053] An output signal 350 of the down- or up-converter 380 can thereafter be fed into a mixer not shown providing a signal showing the frequency difference between the input signal 110 and the reference signal 350. For example, in what is also referred to as photonics mixing, the input signal 310 may comprise a baseband signal, i.e. the signal to be delayed in time, that is modulated to a high frequency wave e.g. in the THz range, and the reference signal 360 may have a slightly different frequency than the high frequency wave of the input signal. A combination of the reference signal and the input signal in a mixer such as a photodiode may later on result in a signal showing the frequency difference between the two THz waves, e.g. a signal in the GHz range such that a microwave signal is generated as a carrier for time shifted baseband signal.

[0054] In the optical domain, and specifically in the case of photonic mixing, the optical reference signal 360 of Figure 10 may not necessarily require a phase shifter 370 but may in a preferred embodiment be delayed in its baseband signal on its carrier but not in the carrier. In order to generate a time delay for the modulated signal i.e. with the origin of the linear phase at 0Hz, a phase offset constant in frequency is preferably added onto the carrier. This phase offset can be implemented on the reference signal 360 directly using another phase modulator 370. To simplify the control of the tunable time delay element, the phase shifter of the modulation unit 330 and the phase shifter 370 can e.g. be driven with a very same control signal by designing the phase shifters such that they provide different phase shifts for the same drive voltage, or by implementing different electronic amplifiers.

[0055] In Figure 11, another tunable time delay element is presented according to an embodiment of the present invention. This embodiment makes use of the basic components of the embodiment shown in Figure 10.

[0056] In a first section 401, an input signal 410 is supplied to a filter unit and tuned in a polarizer 411 of the filter unit to have a 45° degree polarization before entering a polarization maintaining fiber 422 leading to a delay of signals at two outputs of the fiber 422 due to a fiber birefringence between the slow and fast axis. In another polarizer 423, the two signals are then again rotated by 45° degrees so that interferences can take place on the vertical and horizontal polarization to generate two filter signals at the filter unit outputs that lie in two orthogonal polarizations.

[0057] A reference signal 460, e.g. in form of a reference laser signal, is polarized by a polarizer 461 to lay at 45° degrees in order to avoid losses in the last section 403. A coupler 462 combines the complementary spectrum signals lying in two polarizations with the polarized reference signal in order to have a single interconnection between sections 401 and 402 avoiding therefore phase noise.

[0058] In the second section 402, wavelength de-multiplexer 431 is used for splitting the signals again. The filter signals can thus enter a polarization dependent phase modulation unit 430 in order to add the phase shift to one of the polarizations

while the reference signal is supplied to an offset phase modulator 470.

[0059] In another implementation, a polarization beam splitter may be used before the modulation unit 430 in order to simplify the setup. With a proper design of the phase modulation unit 430 and the phase modulator 470 or electrical amplifier, a common control signal 432 can directly drive both modulation unit 430 and modulator 470 as explained earlier. The signals from the modulation unit 430 and the modulator are finally combined in a coupler 433 - which in one embodiment may be a WDM coupler as depicted - before entering a last section 403. In the last section 403, the components 441 and 442 correspond to the components 241 and 242 of Figure 10 in form of a coupler and a mixer, wherein the mixer supplies the output signal 450. In an alternate arrangement, the polarizer 461 may be arranged after the modulator 470.

[0060] In a preferred application, a tunable time delay element according to any of the embodiments is used in a phase array feeder for supplying signals with different delay times to individual antennas of an antenna array, such that a radiation pattern of such phase array takes a desired shape, i.e. a desired direction.

[0061] Figure 12 depicts the building blocks of a phase array feeder according to an embodiment of the present invention. In a first section 501, signal generation and filtering is performed with any filter unit as proposed in the previous embodiments, e.g. such as a filter unit 301 or 401 as comprised in Figures 11 or 12. Accordingly, the filter unit 301 supplies filter signals to a splitter 504. In the splitter 504, the filter signals are split / de-multiplexed into a number of filter signal pairs corresponding to the number of antennas to be driven by the present phase array feeder, e.g. 16 signal pairs for a 4x4 antenna array, or into any desired number. Then, for each antenna to be driven, a phase shift is applied in each modulation units 302 of section 502 to one of the filter signals. If applicable, a phase offset may be applied to a frequency shifted reference signal in these modulation units 302 as well. In the last section 503, the signal pairs supplied by each modulation unit 302 are combined in a combination unit 303 each in order to generate output signals, preferably by using photonic mixing in order to generate microwave output signals. In a preferred embodiment, each output signal drives a corresponding antenna. In case each modulation unit 302 applies a modulation of different magnitude, e.g. a different phase shift to one of the filter signals, the output signals differ in the delay time such that the antennas may generate a directed electromagnetic field.

[0062] In order to simplify a control of such phase array feeder, delays corresponding to two different steering angles - azimuth and elevation - may be evoked in two distinct instances. Figure 13 illustrates a block diagram in section 602 with a corresponding modulation unit such as preferably used in each of the modulation units 302 of Figure 12. In the modulation unit of Figure 13, two steering directions corresponding to the two different steering angles are driven independently. For this purpose, each modulation unit preferably contains two modulation sub-units. Control signals 632x and 632y for the azimuth and elevation angle respectively drive separate phase modulators 630x and 630y for modulating at least one of the filter signals, and possibly in addition drive separate phase modulators 670x and 670y for modulating a reference signal.

[0063] Referring to Figure 13, along one row or one column of the phase array feeder, each antenna preferably is supplied with an output signal of a different delay in time - which preferably are multiples of a basic delay time - depending on the antenna position. In order to control the various delay times directly with a single signal for both angles - azimuth and elevation - it is preferred that the corresponding modulator length - or amplifier gain - is changed depending on the position on the array while keeping a ratio between the modulation of the filter signal and a modulation of the reference signal constant. For the particular case of changing the modulator length, the size of the azimuth modulators 630x and 670x will change along one direction of the array, e.g. x, while the size of the elevation modulators 630y and 670y will change along the second direction of the array, e.g. y, with both the longer size at the edge of the array. Hence, the system can be driven with only one voltage for X and one voltage for Y. The different time delays for the different antenna elements are then created owed to the different sizes. Another improvement of the array driving structure may be to change a sign of the modulator's effect between the left and right side of the array, for e.g. the azimuth modulator, and the upper and lower side, for e.g. the azimuth modulator, in order to reduce maximum delays requested thought the array, e.g. $2\Delta t$ would be replaced by $\pm \Delta t$. In order to decrease the numbers of control units, a wavelength division multiplexing scheme preferably is implemented.

[0064] Figure 14 depicts an application of one or more tunable time delay elements according to an embodiment of the present invention, where a phase array 701 containing a phase array feeder according to Figure 13, for example, is used to combine space-division multiple access (SDMA) with a time division multiplexing (TDM) scheme into a space-time division multiplexing. A transmitter array in the form of an array of antennas comprised in the phase array 701 sends short-pulses to different receivers 702 to 704, e.g. represented by mobile phones of users, each receiver 702 to 704 receiving only one symbol of information at the time. By using such a principle, the bandwidth of an electronic in the receiver can be dimensioned smaller than the bandwidth to be provided in the transmitter, i.e. the phase array 701, thereby avoiding waste of resources as it is nowadays often the case.

[0065] A very similar structure as the one proposed for the phase array embodiments but with a different distribution of the control signals preferably is used to generate an orbital angular momentum (OAM). In this case, a size of the phase shifter - or a gain of an amplifier - may not change along the Cartesian coordinates, e.g. along x and y but along

the polar coordinates, e.g. along radius and angle, in order to generate different OAM modes depending on the applied voltage. Such a system could for example be used to encode information not only on the amplitude and phase of the signal - advanced modulation format - but also on a third axis corresponding to the different OAM modes.

Claims

1. A delay element for delaying an input signal (110) having a frequency spectrum into an output signal (150) representing the input signal delayed in time, comprising:

- a filter unit (120) for splitting the input signal (110) into at least two filter signals to the frequency spectrum of the input signal (110),
- a modulation unit (130) for modulating at least one of the filter signals, and
- a combining unit (140) for combining the at least one modulated filter signal and any non-modulated filter signal into the output signal (150).

2. A delay element according to claim 1, wherein the modulation unit (130) is configured to modulate the one or more filter signals in one or more of the parameters:

- phase;
- amplitude;
- frequency;
- polarization.

3. A delay element according to claim 2,

- wherein the filter unit (120) is configured for splitting the input signal (110) into two filter signals to the frequency spectrum of the input signal (110),
- wherein the modulation unit (130) is configured to modulate a phase φ of one of the filter signals between $-n/2 < \varphi < n/2$ and not to modulate a phase of the other filter signal.

4. A delay element according to claim 2, wherein the modulation unit (130) is configured to modify the parameter to be modulated during an operation of the delay element.

5. A delay element according to any of the preceding claims,

- wherein the filter unit (120) comprises one of:
 - a tunable spatial light modulator,
 - a delay interferometer;
 - a ring resonator.

6. A tunable delay element according to any of the preceding claims, wherein the filter unit (120), the modulation unit (130), and the combining unit (140) are integrated on a common substrate.

7. A delay element according to any one of the preceding claims, wherein the input signal (110), the output signal (150), the filter signals and the one or more modulated filter signals are optical signals.

8. A delay element according to any one of the preceding claims, wherein the input signal (110) is an optical input signal, wherein the filter unit (120) comprises a waveguide section (222) made from a birefringent material for splitting the optical input signal into two optical filter signals of different polarization, wherein the modulation unit (130) comprises a polarization sensitive phase modulator (230) for offsetting the phase in one of the optical filter signals only, wherein the combination unit (140) comprises an optical mixer (242) for mixing the optical filter signal and the

modulated optical filter signal.

9. A delay element according to claim 8,
 wherein the filter unit (120) comprises a polarization controller (211) for polarizing the optical input signal prior to
 being propagated to the waveguide section (222), and comprises another polarization controller (223) for polarizing
 the two optical filter signals of different polarities supplied by the waveguide section (222), and
 wherein the combination unit (140) comprises a polarization controller (241) for polarizing the filter and the modulated
 optical filter signal, and comprises the mixer (242) for mixing the signals received from the polarizer (241) for
 generating the output signal (150) being an optical output signal.

10. A delay element according to claim 8 or claim 9,
 comprising a single waveguide for propagating the optical input signal, the optical output signal, the optical filter
 signals and the one or more modulated filter optical signals, and
 wherein the filter unit (120), the modulation unit (130), and the combination unit (140) act on the respective optical
 signals propagated by the single waveguide.

11. A delay element according to any one of the preceding claims, comprising
 a reference signal generator for generating a reference signal (360) comprising a frequency offset with respect to
 the frequency spectrum of the input signal (110),
 a coupler (380) for coupling the output signal (150) and the reference signal (360) or a signal derived from the
 reference signal (360), and
 in particular comprising another modulator (370) for applying a phase shift to the reference signal (360), and
 in particular wherein the reference signal (360) is an optical signal, and in particular is a laser signal.

12. A phase array feeder for processing signals to be supplied to an array of n antennas, the phase array feeder
 comprising a delay element according to any one of the preceding claims for supplying the output signal (150) of
 which delay element to one of the n antennas of the array, the phase array feeder comprising

- n-1 additional modulation units (302),
- n-1 additional combination units (303),
- a unit (504) for supplying the filter signals provided by the filter unit (301) of the delay element to each of the
 n-1 additional modulation units (302),
 wherein each additional modulation unit (302) is configured to modulate at least one of the filter signals supplied,
 and
 wherein each additional combining unit (303) is configured to combine the at least one modulated filter signal
 of the assigned additional modulation unit (302) and any filter signal not modulated by the assigned additional
 modulation unit into a corresponding output signal to be supplied to an associate antenna of the array, and
 in particular wherein the n-1 additional modulation units (302) are configured to modulate one of the filter signals
 in phase by a different phase offset.

13. Usage of a delay element according to any one of the preceding claims 1 to 12 in one of a

- phase array feeder;
- a clock recovery system;
- modulation format generator;
- a tunable interferometer
- a multiplexer.

14. Method for delaying an input signal having a frequency spectrum, comprising:

- splitting the input signal (110) into at least two filter signals to the frequency spectrum of the input signal (110),
- modulating at least one of the filter signals, and
- combining the at least one modulated filter signal and any non-modulated filter signal into an output signal
 (150) representing the input signal delayed in time.

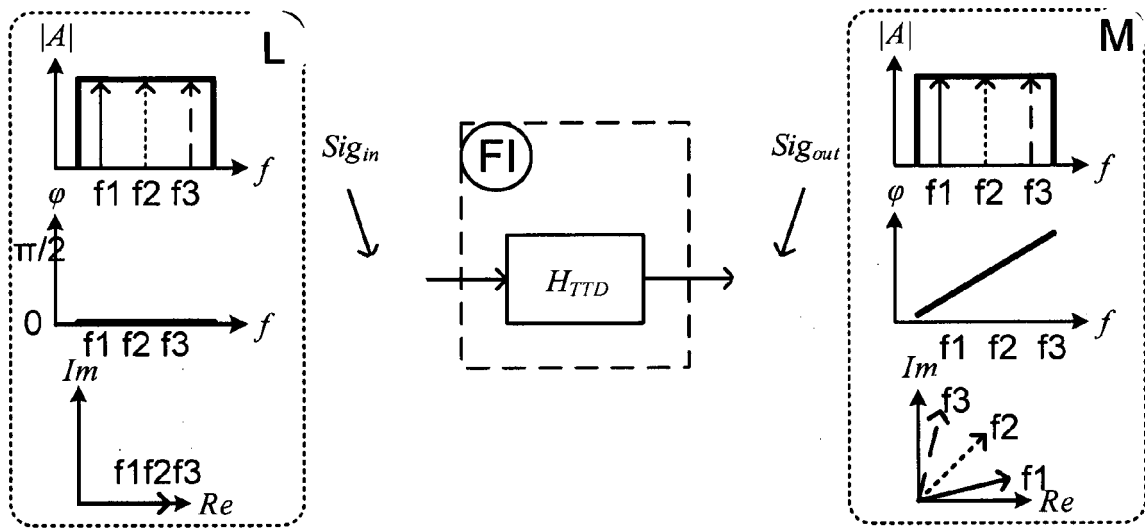


FIG. 1

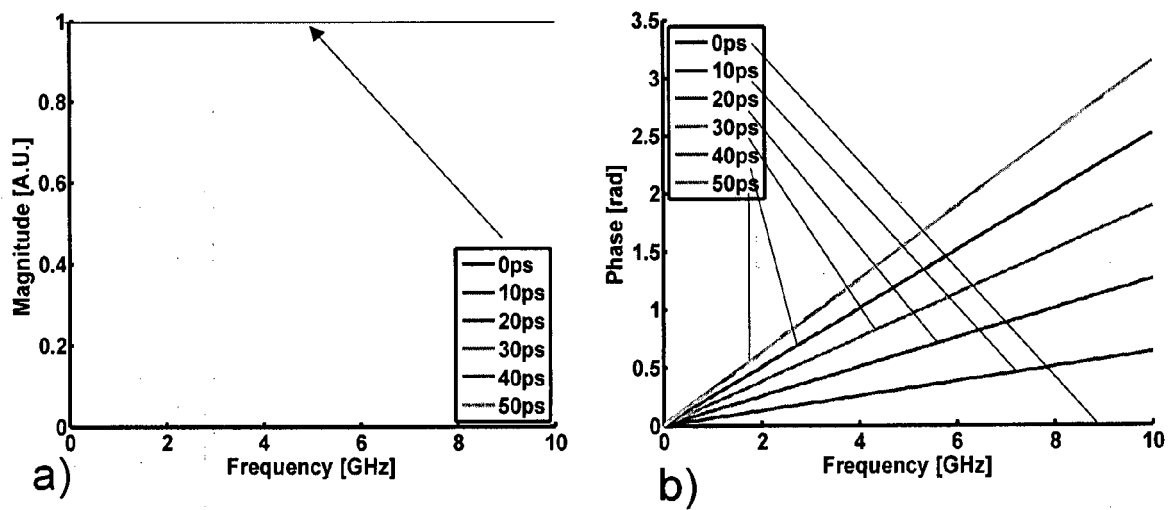


FIG. 2

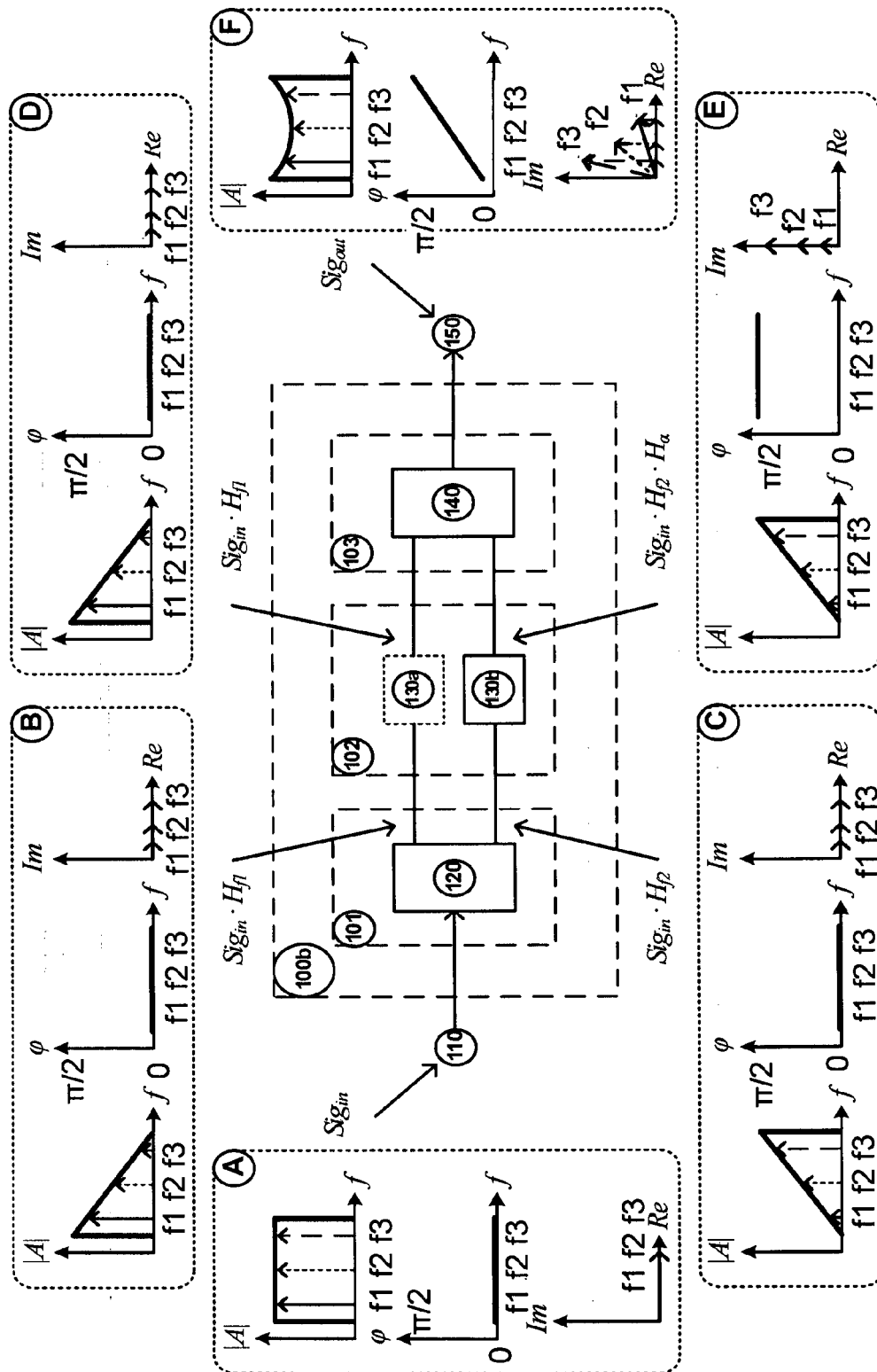


FIG. 3

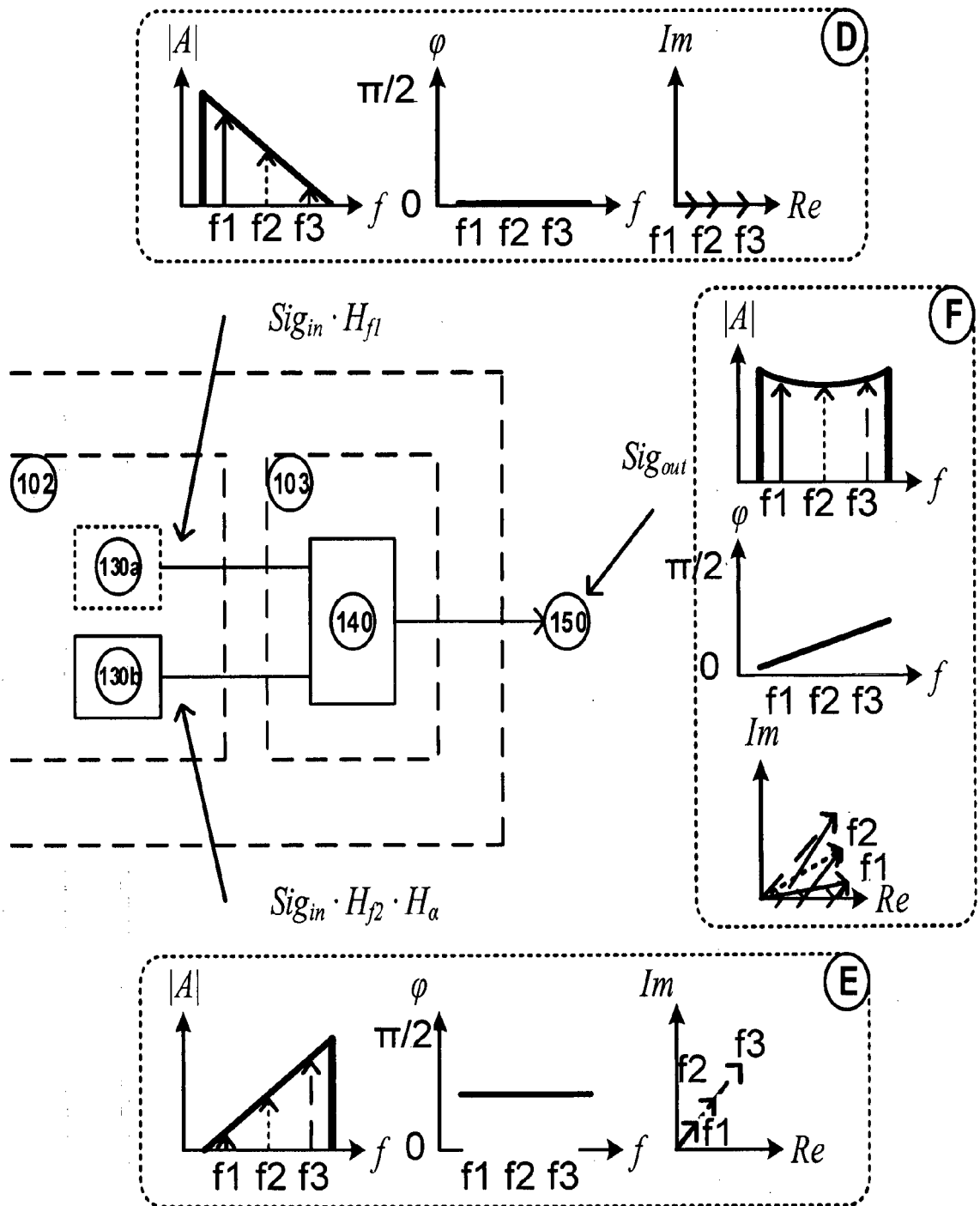


FIG. 4

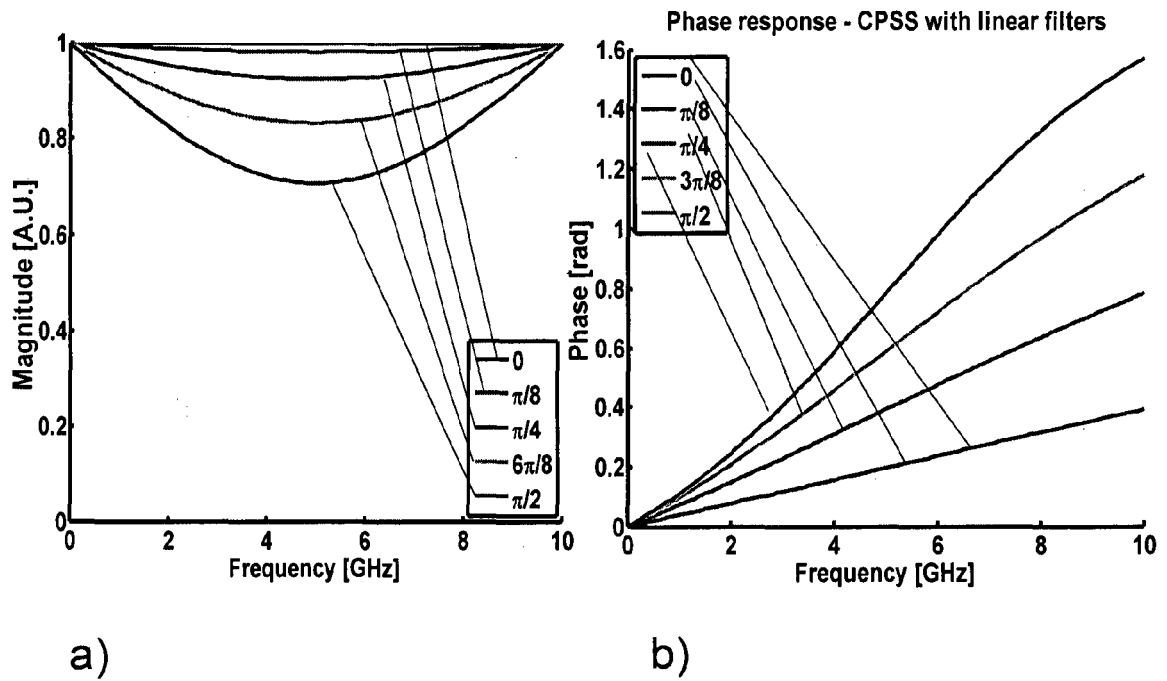


FIG. 5

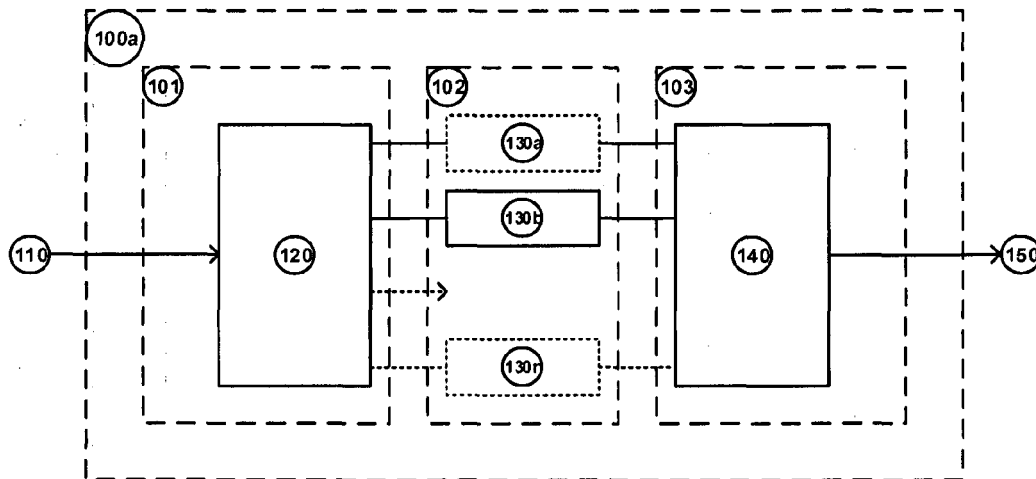


FIG. 6

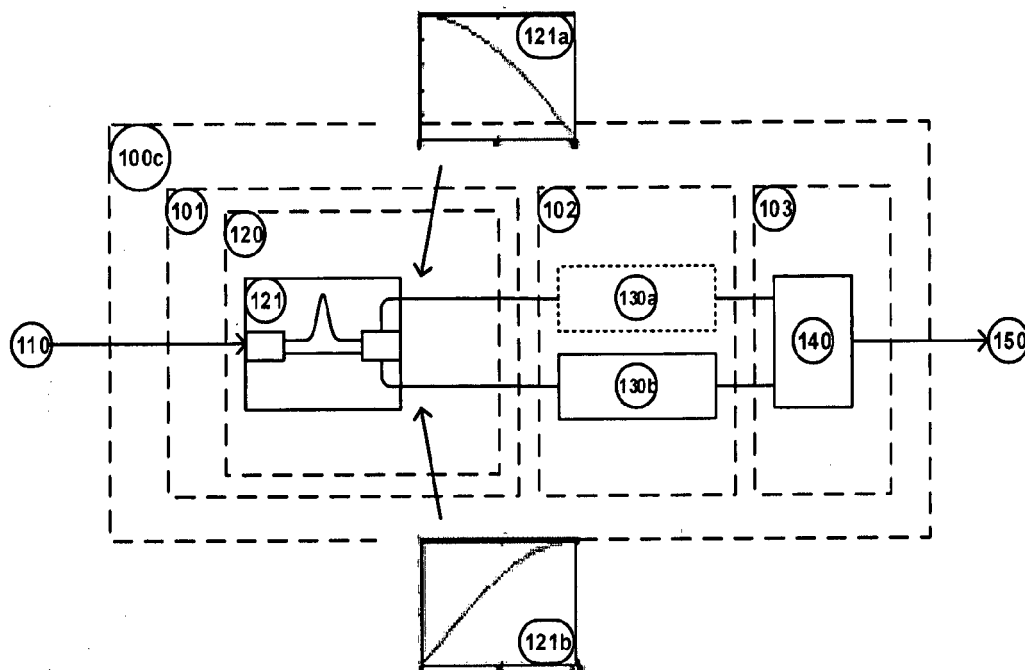


FIG. 7

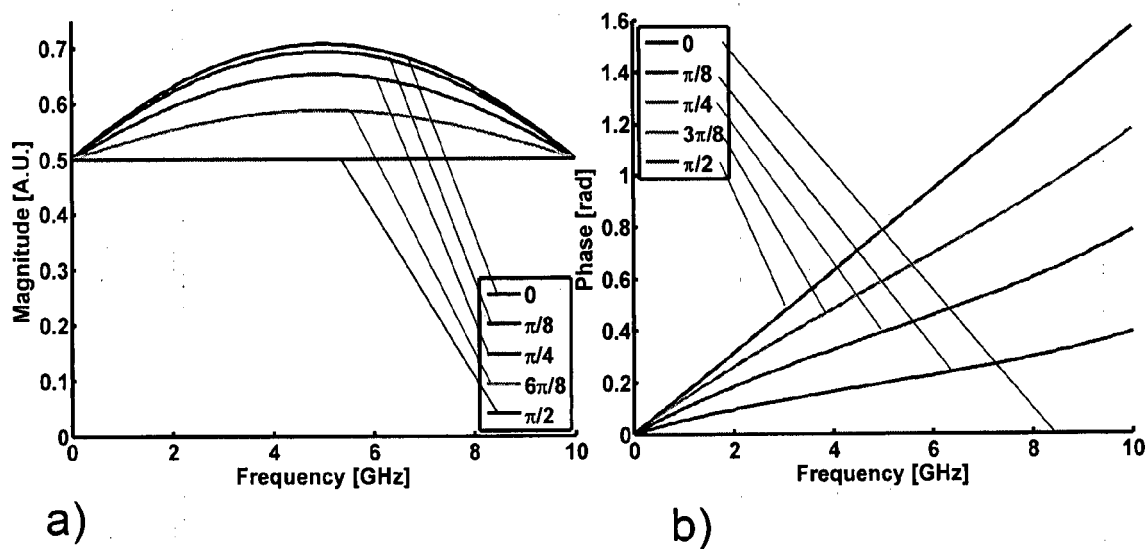


FIG. 8

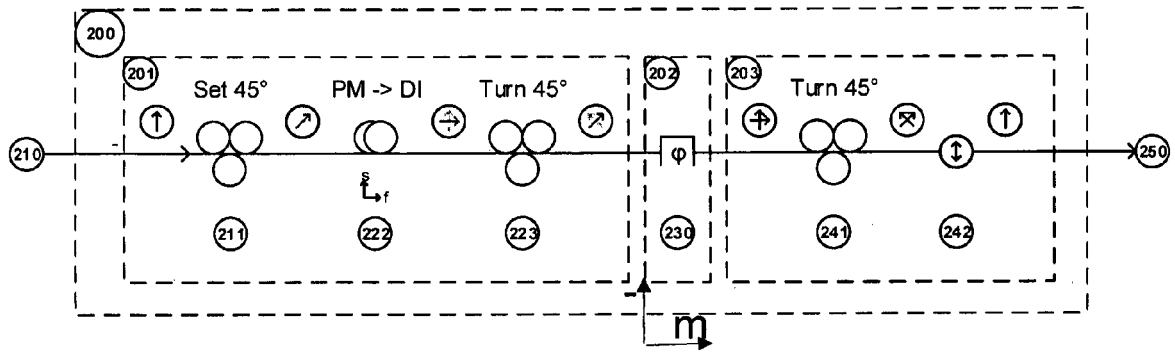


FIG. 9

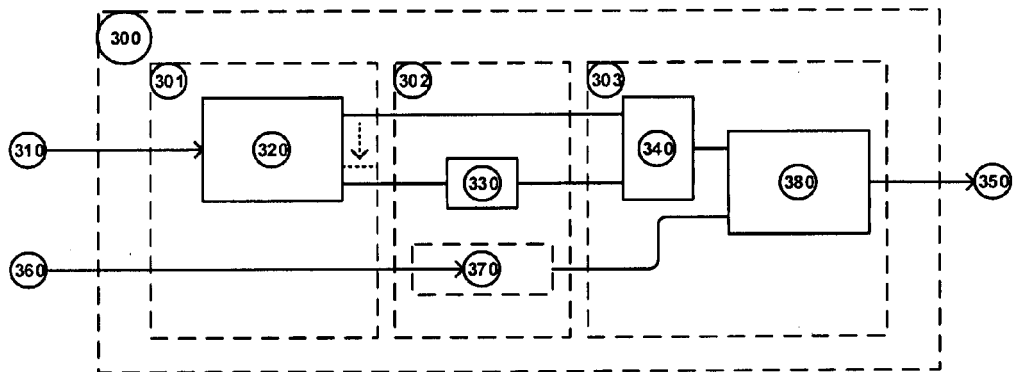


FIG. 10

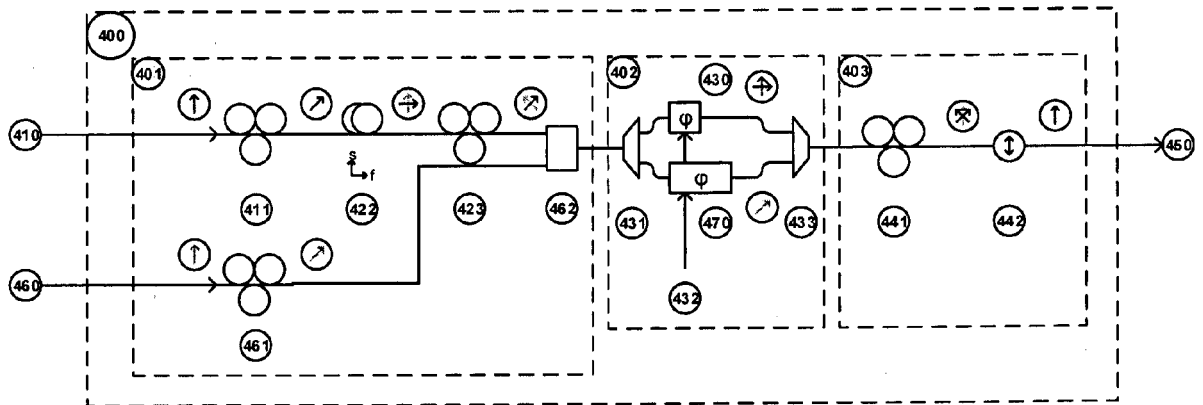


FIG. 11

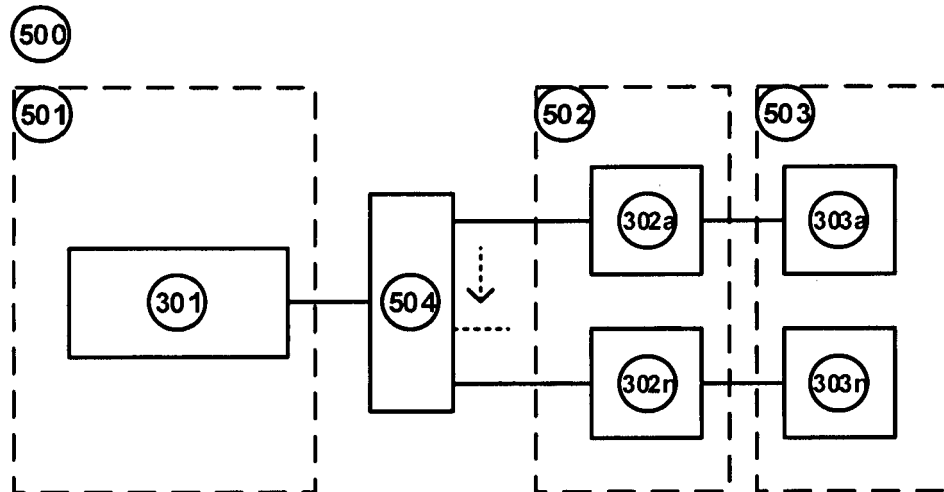


FIG. 12

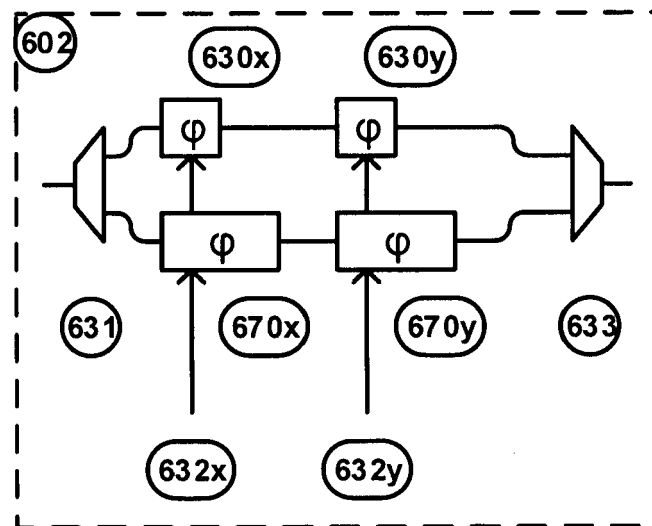


FIG. 13

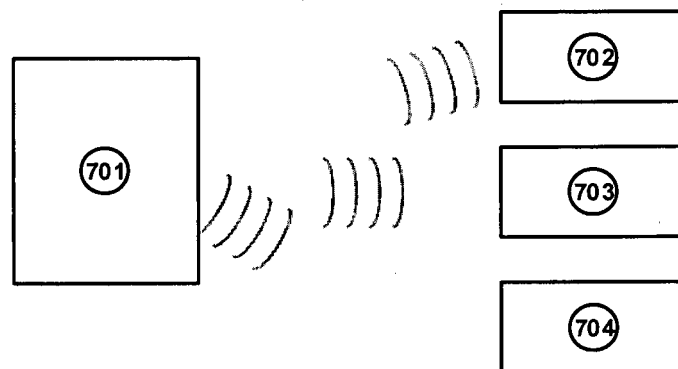


FIG. 14



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Y	* paragraphs [0014], [0018], [0019];	8-10	
A	figure 1 * * paragraphs [0045], [0046]; figure 3 *	11	
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Y	* column 1, lines 14-17,33-64; figure 1 *	8-10	
A	* column 5, line 56 - column 6, line 27; figure 2 * * column 11, line 63 - column 12, line 21; figure 12 *	11	
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A	* column 5, lines 17-26; figure 3 *	4,8-11	
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A	* paragraph [0005] * * paragraphs [0090], [0091], [0094]; figure 10 *	1-7, 11-14	TECHNICAL FIELDS SEARCHED (IPC) G02B
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Place of search Munich		Date of completion of the search 22 January 2015	Examiner Martínez Martínez, J
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			

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