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(54) **SYSTEM AND METHOD FOR ADJUSTABLE BEAM STEERING IN RADIO FREQUENCY DOMAIN**

(57) The invention provides a system (10) for adjustable beam steering in radio frequency domain. The system (10) comprises at least one phase shifter (14) that is established by a flexible liquid metal microfiber (16). The phase shifter (14) is fastened to a displacement

member (22) that is configured to adapt the length of the flexible liquid metal microfiber (16). Further, a method of adjustable beam steering in radio frequency domain is described.

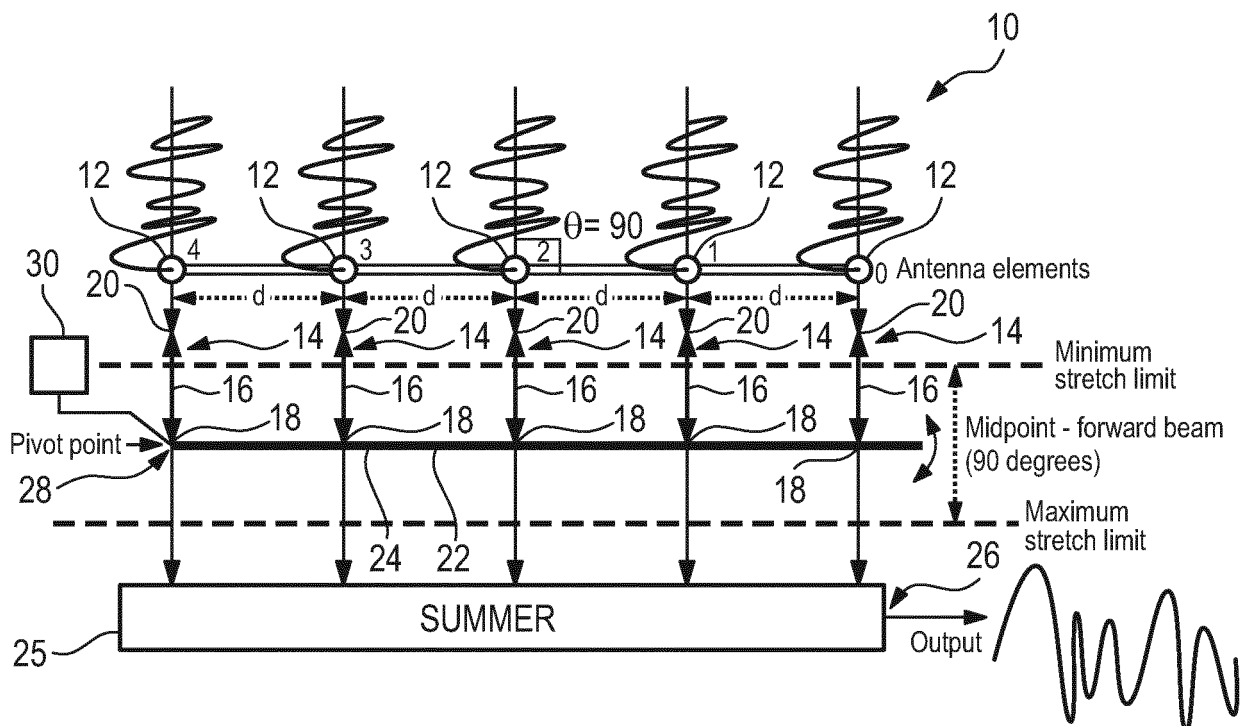


Fig. 2

Description

[0001] The invention relates to a system for adjustable beam steering in radio frequency domain. Further, the invention relates to a method of adjustable beam steering in radio frequency domain.

[0002] In the state of the art, beamformers are typically used for beam steering tests in order to generate plane waves at certain angles for testing devices under test, for instance mobile devices or similar. The general concept of beam steering is illustrated in Figure 1.

[0003] Typically, a linear array beamformer is used that consists of a line of antennas that are separated from each other by half a wavelength of the test signals used. In 5G systems and beyond, beam forming or beam steering is an important feature and, therefore, respective characteristics of the devices under test have to be tested.

[0004] In general, beam steering to a particular direction is achieved by delaying the arrival of a planar wave front at each antenna by specific amounts, e.g. by using delay elements. Then, all the signals collected at the antenna from a particular direction are in phase and summed to maximize the received signal power at the output. Generally, beam steering can be performed at radio frequency (RF) domain at the antennas or at base-band after digitalization of the signals.

[0005] However, the concepts known in the state of the art relate to complex and heavy beamformers which makes it difficult to expand the respective beamformers for a larger number of antennas.

[0006] Accordingly, there is a need for a simple, low-complex and light-weight beamformer that can be manufactured at low costs.

[0007] The invention provides a system for adjustable beam steering in radio frequency (RF) domain. The system comprises at least one phase shifter that is established by a flexible liquid metal microfiber (FLMM). The phase shifter is fastened to a displacement member that is configured to adapt the length of the flexible liquid metal microfiber.

[0008] Further, the invention provides a method of adjustable beam steering in radio frequency domain. The method comprises the steps of:

- Providing a system that comprises at least one phase shifter that is established by a flexible liquid metal microfiber, and
- Adapting, by means of a displacement member, the length of the flexible liquid metal microfiber, thereby setting a delay introduced by the phase shifter.

[0009] The invention is based on the finding that a flexible liquid metal microfiber (FLMM) is used as a delay line in order to introduce a delay, thereby shifting the phase of the signal in the radio frequency domain. A different delay is introduced by adapting the length of the

flexible liquid metal microfiber, thereby adapting the properties of the liquid metal of the flexible liquid metal microfiber. Hence, a unique property of the flexible liquid metal microfiber is used for setting the delay introduced by the flexible liquid metal microfiber so as to shift the phase. Generally, the at least one flexible liquid metal microfiber may be stretched and/or compressed in order to adapt the length. Depending on the amount of length adaption, a different delay is introduced, thereby shifting the phase of the respective signal processed by the flexible liquid metal microfiber differently in a defined manner. Accordingly, the system is enabled to perform beam steering in an appropriate manner.

[0010] Generally, a flexible liquid metal microfiber has electrical contacts at its ends, e.g. metal contacts. In addition, the flexible liquid metal microfiber comprises a flexible plastic core material for the liquid metal such that the liquid metal is confined by the flexible plastic core material. The electrical contacts are in connection with the liquid metal confined, thereby ensuring a continuous line. The flexible plastic core material is elastic, thereby ensuring that the flexible liquid metal microfiber can be adapted with regard to its length in a reversible manner. Once no force is applied to the flexible liquid metal microfiber, the flexible liquid metal microfiber gets back into its original state due to its elastically reversible properties.

[0011] An aspect provides that the phase shifter is fastened to the displacement member via a first end of the flexible liquid metal microfiber. Thus, the adaption of the length is introduced via the first end of the flexible liquid metal microfiber, which is associated with an electrical contact of the respective flexible liquid metal microfiber. The second end of the flexible liquid metal microfiber, which is opposite to the first end, may be fixedly located, thereby ensuring a length adaption when applying a force on the first end via the displacement member.

[0012] Another aspect provides that the phase shifter is fastened to an antenna element via a second end of the flexible liquid metal microfiber. Accordingly, the flexible liquid metal microfiber is fixedly connected with the antenna element via the other electrical contact. This ensures that the relative orientation of the antenna element(s) remains the same even though the length of the flexible liquid metal microfiber is adapted by means of the displacement member.

[0013] Generally, the electrical contacts are not elastic such that they can be used for fastening purposes. Hence, the first and second ends may be established by the electrical contacts of the flexible liquid metal microfiber, respectively.

[0014] According to an example, the displacement member is configured to be pivoted about a pivot point, thereby adapting the length of the flexible liquid metal microfiber. The pivoting ensures that the flexible liquid metal microfiber can be adapted with regard to its length easily. Depending on the pivot angle, a different delay is introduced, as the length adaption also depends on the pivot angle.

[0015] The pivot point may be set at a location that is halfway between a minimum stretch limit and a maximum stretch limit of the flexible liquid metal microfiber. Particularly, in case of more than one flexible liquid metal microfiber, the flexible liquid metal microfiber farthest from the pivot point and/or the flexible liquid metal microfiber having the smallest distance between the minimum stretch limit and the maximum stretch limit is the one that is used for locating the pivot point appropriately, namely halfway between the respective stretch limits. Generally, this ensures that a maximal scope of adjustment can be obtained, resulting in maximum scope of beam steering.

[0016] For instance, the system comprises an actuator that is configured to actuate the displacement member. Particularly, the displacement member is pivoted by means of the actuator about the pivot point. Thus, an electrically controlled movement or rather length adaption is ensured, which allows to set different defined delays by means of the flexible liquid metal microfiber in a defined and controlled manner.

[0017] Alternatively, the displacement member may be pivoted and/or actuated manually.

[0018] A further aspect provides that the system comprises more than one flexible liquid metal microfiber, wherein the flexible liquid metal microfibers are spaced to each other at a predetermined distance. Particularly, the predetermined distance is half the wavelength of a test signal used, namely the test signal used for testing the beam steering properties of a device under test. Generally, a progressive delay for each antenna element associated with the several flexible liquid metal microfibers can be obtained.

[0019] Another aspect provides that the system comprises more than two flexible liquid metal microfibers, wherein neighbored flexible liquid metal microfibers are spaced to each other at a predetermined distance that is equal for each pair of neighbored flexible liquid metal microfibers. Accordingly, all flexible liquid metal microfibers are distanced from each other by the same distance, particularly half the wavelength of the test signal used for testing purposes.

[0020] Another aspect provides that the system comprises more than one flexible liquid metal microfiber, wherein each of the flexible liquid metal microfibers are fastened to a common displacement member. Thus, the flexible liquid metal microfibers can be moved or rather displaced commonly, namely by actuating the common displacement member. The common displacement member can be pivoted about the pivot point, thereby adapting the length of the different flexible liquid metal microfibers differently. However, the different length adaptations of the flexible liquid metal microfibers depend on each other, as all of the flexible liquid metal microfibers are connected to the same common displacement member.

[0021] In other words, the system may comprise several flexible liquid metal microfibers that are adapted with regard to their lengths by means of the common displacement member to which the flexible liquid metal microfibers are commonly fastened.

[0022] For instance, the common displacement member can be a rod.

[0023] Alternatively, each flexible liquid metal microfiber is fastened to an own displacement member. Hence, more complex beam contours can be obtained, as a sophisticated actuating of the different flexible liquid metal microfibers can be done. In fact, the flexible liquid metal microfibers are decoupled from each other, thereby ensuring an individual length adaption of each flexible liquid metal microfiber. This may result in different delays introduced. In fact, the flexible liquid metal microfibers can be adapted with regard to their lengths independently of each other. In other words, the system may comprise several flexible liquid metal microfibers that are adapted with regard to their lengths individually by means of the own displacement members to which the flexible liquid metal microfibers are individually fastened.

[0024] Generally, the flexible liquid metal microfibers can be fastened to any type of antenna array in case own displacement members are provided, e.g. a linear antenna array, a circular antenna array or other shapes of the antenna array.

[0025] Furthermore, the distance(s) among the flexible liquid metal microfibers can be set independently, particularly different to half wavelength distance.

[0026] In general, the own displacement member, namely the independent displacement member, can be controlled by means of an algorithm. The algorithm controls the respective length adaption. Hence, the algorithm controls a specific antenna beamforming, e.g. radiation pattern. Particularly, the length adaption is controlled such that an antenna pattern is obtained which may be used for cancellation of interference from specific directions.

[0027] Moreover, the length adaption(s) may be done in three-dimensions. For instance, the length adaption(s) may take place in azimuth and in elevation.

[0028] In other words, the displacement members may be configured to adapt the lengths of the flexible liquid metal microfibers towards different directions. Particularly, the flexible liquid metal microfibers are located in different directions.

[0029] The flexible liquid metal microfiber may comprise a eutectic alloy, particularly at least one of an eutectic Gallium-Indium (EGaln) alloy or an eutectic Gallium-Sn (EGalnSn) alloy. These alloys are able to conduct electricity whilst in a liquid state at room temperature. Accordingly, liquid metal can be utilized to replace mercury due to its low vapor pressure, low toxicity, low viscosity and metallic electrical conductivity performance. Since the liquid metal is used inside a stretchable microfiber elastomer, the liquid metal can be easily adapted to various lengths and the elastomer will return to its original length when released.

[0030] Generally, the eutectic alloy enlarges the temperature range of flexibility of the flexible liquid metal microfiber.

crofiber.

[0031] The flexible liquid metal microfiber has a linear characteristic of phase versus extension. Particularly, the characteristic is independent of the frequency of the test signal used. Only the slope of the linear characteristic is different for different frequencies, but the general characteristic, namely the linear characteristic, remains the same for all of the frequencies. This is ensured since the waveform goes through a greater phase change at higher frequencies for the same length adaption of the flexible liquid metal microfiber.

[0032] Moreover, the flexible liquid metal microfiber may have a coaxial structure with characteristic impedance of 50 ohm over the stretch limits. Hence, a mismatching of antennas can be avoided, thereby ensuring to obtain an optimized input output ratio.

[0033] In fact, the system and the method ensure beam steering at low complexity and in a lightweight manner.

[0034] Generally, the system may have at least two lines, wherein one could be a fixed line and the other one is established by the flexible liquid metal microfiber.

[0035] Further aspects and advantages of the claimed subject matter will become more readily appreciated as the same become better understood by reference to the following description when taken in conjunction with the accompanying drawings. In the drawings,

- Figure 1 shows a linear array beamformer according to the state of the art,
- Figure 2 shows an overview of a system according to the invention in a first state,
- Figure 3 shows the system of Figure 2 in a second state,
- Figure 4 shows the system of Figure 2 in a third state,
- Figure 5 shows an overview of the flexible liquid metal microfibers used by the system of Figures 2 to 4, and
- Figure 6 shows an overview of phase versus length adaption at different frequencies for a flexible liquid metal microfiber use by the system of Figures 2 to 4.

[0036] In Figure 1, a linear array beamformer according to the state of the art is shown which is used to describe the concept of beam steering. A planar wave front arrives at angle θ onto a linear array of antennas indicated by 0 to 4. The wave front first arrives at antenna 0 and arrives at antenna 4 last. Using basic trigonometry, the distances the wave front has to travel to each antenna can be calculated. By applying the proper amount of delays by delay elements (D0 to D5), all the wave fronts are in-phase at the input of a summer circuit, thereby maximizing the signal output at angle θ . Using Antenna 4 as a reference point with delay D4=0, the delays must

increase from left (D3) to right (D0) to maximize the output signal at angle θ . At different angles of arrival, the values of D0 to D4 must be adjusted accordingly.

[0037] In practice, this is typically achieved by using delay lines, namely either electronically controlled mechanically driven trombone lines or PIN diode delay switches. The PIN diode delay ensures fast setting (< 50 ms), but only works below 4 GHz compared to up to 18 GHz for the trombone lines, which however can last up to 6500 ms with respect to setting.

[0038] In Figure 2, a system 10 for adjustable beam steering in a radio frequency domain according to the invention is shown.

[0039] In the shown embodiment, the system 10 comprises five antenna elements 12 that are each connected to a phase shifter 14 established by a flexible liquid metal microfiber 16.

[0040] The flexible liquid metal microfibers 16 each have a first end 18 and a second end 20. The flexible liquid metal microfibers 16 are connected to the respective antenna elements 12 via the second ends 20 (directly). Via the first ends 18, the flexible liquid metal microfibers 16 are fastened (directly) to a displacement member 22.

[0041] In the shown embodiment, the displacement member 22 is established by means of a common displacement member 24, e.g. a rod.

[0042] In an alternative embodiment, several displacement members 22 may be provided such that each of the flexible liquid metal microfibers 16 is associated with its own displacement member 22. Hence, a sophisticated beam steering can be established, as the respective flexible liquid metal microfibers 16 can be adapted with regard to their lengths individually. The respective length adaption may be realized by a length adaption, for instance by means of a linear displacement of the flexible liquid metal microfibers 16 rather than a pivoting movement. Accordingly, the individual flexible liquid metal microfibers 16 which are decoupled from each other with regard to their length adaptations can be stretched and/or compressed individually, particularly simultaneously. In other words, one of the flexible liquid metal microfibers 16 may be stretched, whereas the neighbored one may be compressed. Hence, the system 10 may generally be configured to stretch one of the flexible liquid metal microfibers 16 and to compress the neighbored flexible liquid metal microfiber 16.

[0043] Irrespective of the specific configuration of the displacement member(s) 22, the phase shifters 14 are electrically connected to a summer circuit 25 such that the signals received via the antenna elements 12 and processed by the flexible liquid metal microfibers 16 are summed in the summer circuit 25. The summer circuit 25 has an output 26 via which the summed signal can be outputted.

[0044] As shown and indicated by the arrow in Figure 2, the displacement member 22 is configured to be pivoted about a pivot point 28, thereby adapting the respec-

tive lengths of the flexible liquid metal microfibers 16 differently, but dependent on each other as also shown in Figure 3 and 4 that illustrate the system 10 in two different other states, namely maximum stretching (Figure 3) and minimum stretching (Figure 4) which will be discussed hereinafter.

[0045] From Figures 2-4, it becomes obvious that the displacement member 22 can be pivoted within ranges that are associated with a minimum stretch limit and a maximum stretch limit of one of the flexible liquid metal microfibers 16, namely the one that is located farthest from the pivot point 28. In the shown embodiment, it is the flexible liquid metal microfiber 16 associated with the antenna element 12 that is labelled with "0" on the right of Figures 2 to 4. The respective stretch limits are indicated in Figures 2 to 4 by the dashed lines as well. Accordingly, it becomes obvious that the respective flexible liquid metal microfiber 16 is stretched to the maximum stretch limit in Figure 3, whereas the respective flexible liquid metal microfiber 16 is compressed to its maximum ("minimum stretch limit") in Figure 4. These different states result in beam steering to the right or rather to the left, as shown in Figures 3 and 4 appropriately.

[0046] Furthermore, the pivot point 28 is set at a location that is halfway between a minimum stretch limit and a maximum stretch limit of the respective flexible liquid metal microfiber 16, namely the one that is located farthest away from the pivot point 28.

[0047] Alternatively, the flexible liquid metal microfiber 16 is taken as a reference that has the smallest distance between its minimum stretch limit and its maximum stretch limit in case of different lengths adaptations of the flexible liquid metal microfibers 16.

[0048] The displacement member 22 may be displaced manually.

[0049] Alternatively, an actuator 30 may be provided that is configured to actuate the displacement member 22, thereby pivoting the displacement member 22 about the pivot point 28.

[0050] The flexible liquid metal microfibers 16 are spaced to each other at a predetermined distance d that may correspond to half the wavelength of the test signals used for testing a device under test. Particularly, neighbored flexible liquid metal microfibers 16 are each spaced by the predetermined distance d as indicated in Figures 2 to 4.

[0051] In Figure 5, one of the flexible liquid metal microfibers 16 is shown in three different lengths, e.g. a compressed state (A), a normal state (B), and a stretched state (C).

[0052] The flexible liquid metal microfiber 16 comprises a first electrical contact 32 and a second electrical contact 34 that are in contact with a liquid metal 36 confined within a stretchable elastomer 38. The liquid metal 36 may be a eutectic alloy, particularly at least one of an eutectic Gallium-Indium (EGaln) alloy or an eutectic Gallium-Sn (EGalnSn) alloy.

[0053] Generally, the liquid metal 36, particularly its

state when the respective flexible liquid metal microfiber 16 is stretched or compressed, causes a respective delay when processing the signal, thereby ensuring the beam steering functionality of the system 10.

[0054] As shown in the diagram of Figure 6, the flexible liquid metal microfiber 16, particularly the liquid metal 36, has a linear characteristic of phase vs. extension such that the phase alters in a linear manner with the length adaption introduced, e.g. the stretching and/or compression. Particularly, the linear characteristic is independent of the frequency used by the test signal, as only the slope of the linear characteristic changes with frequency.

[0055] Moreover, the flexible liquid metal microfibers 16 may have a coaxial structure with characteristic impedance of 50 ohm over their stretch limits, thereby ensuring a matching. Otherwise, impedance matching components will be needed.

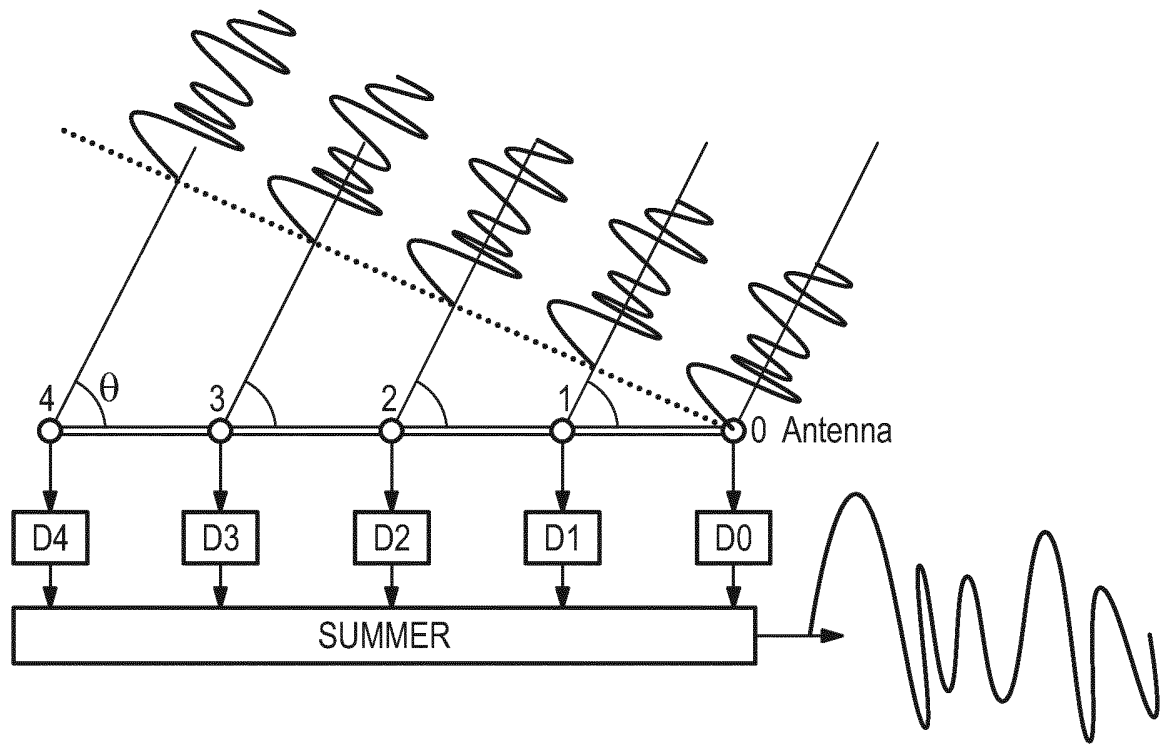
Claims

1. A system for adjustable beam steering in radio frequency domain, the system (10) comprises at least one phase shifter (14) that is established by a flexible liquid metal microfiber (16), and wherein the phase shifter (14) is fastened to a displacement member (22) that is configured to adapt the length of the flexible liquid metal microfiber (16).
2. The system according to claim 1, wherein the phase shifter (14) is fastened to the displacement member (22) via a first end (18) of the flexible liquid metal microfiber (16).
3. The system according to claim 1 or 2, wherein the phase shifter (14) is fastened to an antenna element (12) via a second end (20) of the flexible liquid metal microfiber (16).
4. The system according to any of the preceding claims, wherein the displacement member (22) is configured to be pivoted about a pivot point (28), thereby adapting the length of the flexible liquid metal microfiber (16).
5. The system according to any of the preceding claims, wherein the pivot point (28) is set at a location that is half way between a minimum stretch limit and a maximum stretch limit of the flexible liquid metal microfiber (16), particularly, in case of more than one flexible liquid metal microfibers (16), the flexible liquid metal microfiber (16) farthest from the pivot point (28) and/or the flexible liquid metal microfiber (16) having the smallest distance between the minimum stretch limit and the maximum stretch limit.
6. The system according to any of the preceding claims, wherein the system (10) comprises an actuator (30)

that is configured to actuate the displacement member (22), particularly to pivot the displacement member (22) about the pivot point (28).

7. The system according to any of the preceding claims, wherein the system (10) comprises more than one flexible liquid metal microfiber (16), and wherein the flexible liquid metal microfibers (16) are spaced to each other at a predetermined distance, particularly wherein the predetermined distance is half the wavelength of a test signal used. 5
8. The system according to any of the preceding claims, wherein the system (10) comprises more than two flexible liquid metal microfibers (16), and wherein neighbored flexible liquid metal microfibers (16) are spaced to each other at a predetermined distance which is equal for each pair of neighbored flexible liquid metal microfibers (16). 10
9. The system according to any of the preceding claims, wherein the system (10) comprises more than one flexible liquid metal microfiber (16), and wherein each of the flexible liquid metal microfibers (16) are fastened to a common displacement member (24). 15
10. The system according to any of the preceding claims, wherein each flexible liquid metal microfiber (16) is fastened to an own displacement member (22). 20
11. The system according to any of the preceding claims, wherein the flexible liquid metal microfiber (16) comprises a eutectic alloy, particularly at least one of an eutectic Gallium-Indium (EGaIn) alloy or an eutectic Galinstan (EGaInSn) alloy. 25
12. The system according to any of the preceding claims, wherein the flexible liquid metal microfiber (16) has a linear characteristic of phase versus length variation, particularly independent of the frequency. 30
13. The system according to any of the preceding claims, wherein the flexible liquid metal microfiber (16) has a coaxial structure with characteristic impedance of 50 Ohms over the stretch limits. 35
14. A method of adjustable beam steering in radio frequency domain, with the following steps: 40
 - Providing a system (10) that comprises at least one phase shifter (14) that is established by a flexible liquid metal microfiber (16), and 45
 - Adapting, by means of a displacement member (22), the length of the flexible liquid metal microfiber (16), thereby setting a delay introduced by the phase shifter (14). 50
15. The method of claim 14, wherein the system (10) 55

comprises several flexible liquid metal microfibers (16), and wherein the several flexible liquid metal microfibers (16) are adapted with regard to their lengths individually by means of own displacement members (22) to which the flexible liquid metal microfibers (16) are individually fastened or wherein the several flexible liquid metal microfibers (16) are adapted with regard to their lengths by means of a common displacement member (24) to which the flexible liquid metal microfibers (16) are commonly fastened.



-State of the art-

Fig. 1

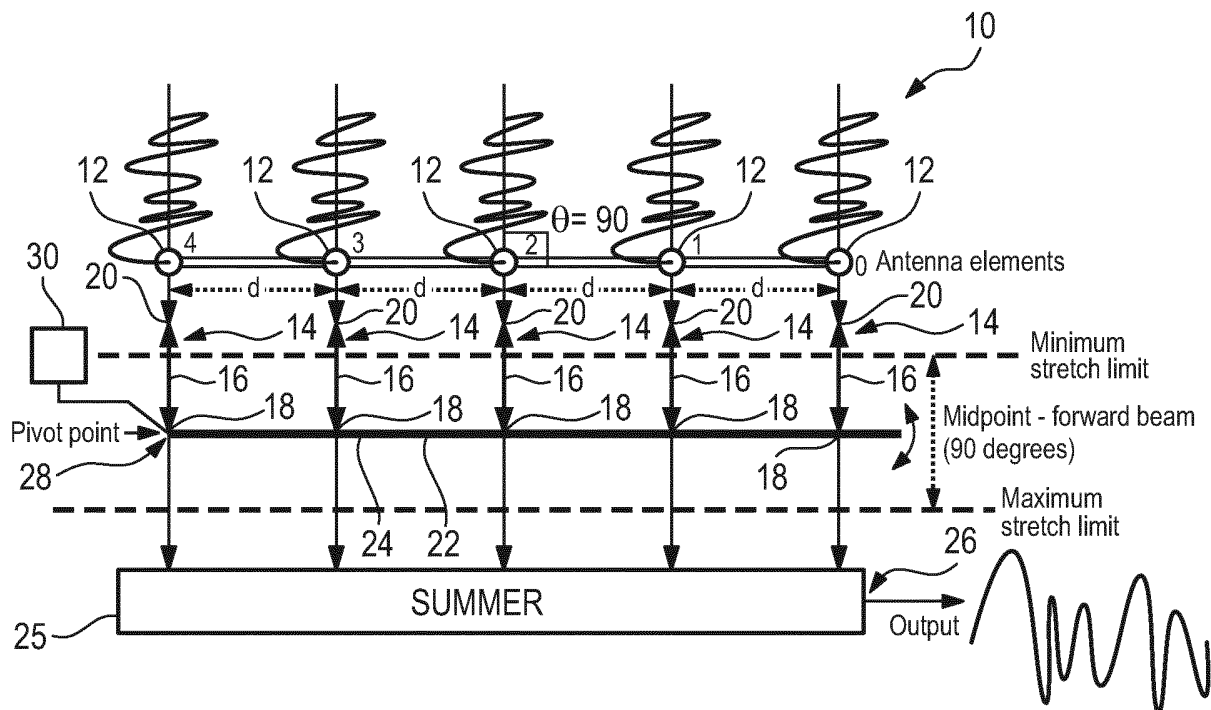


Fig. 2

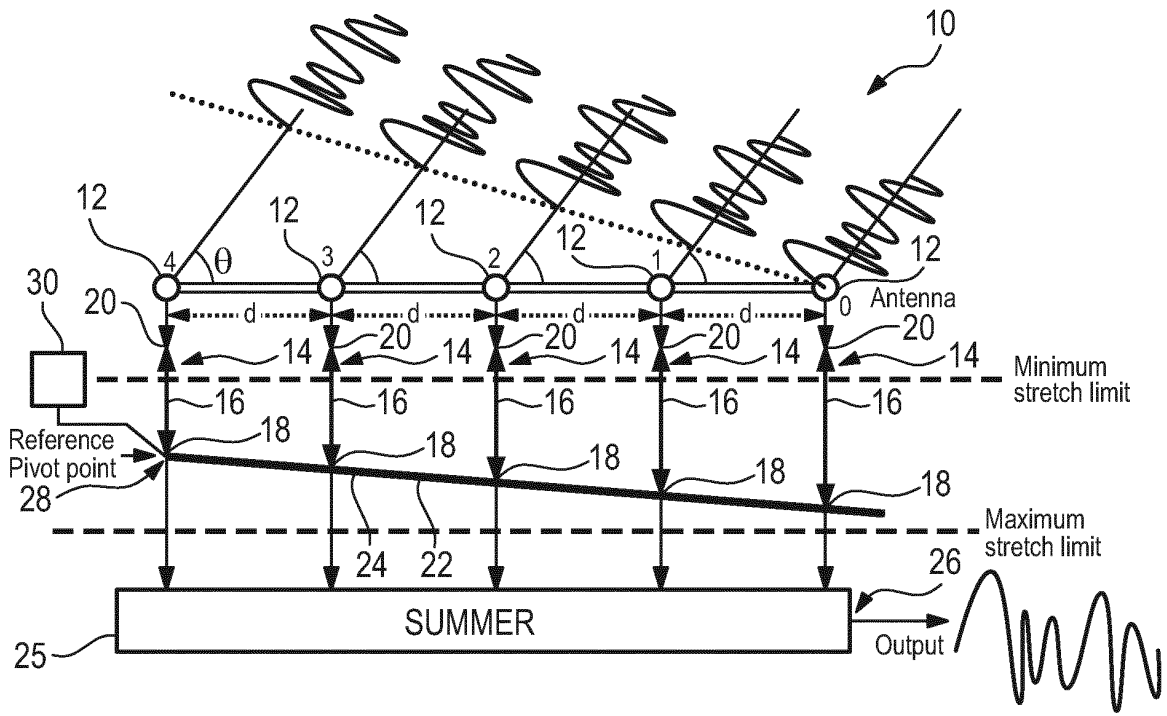


Fig. 3

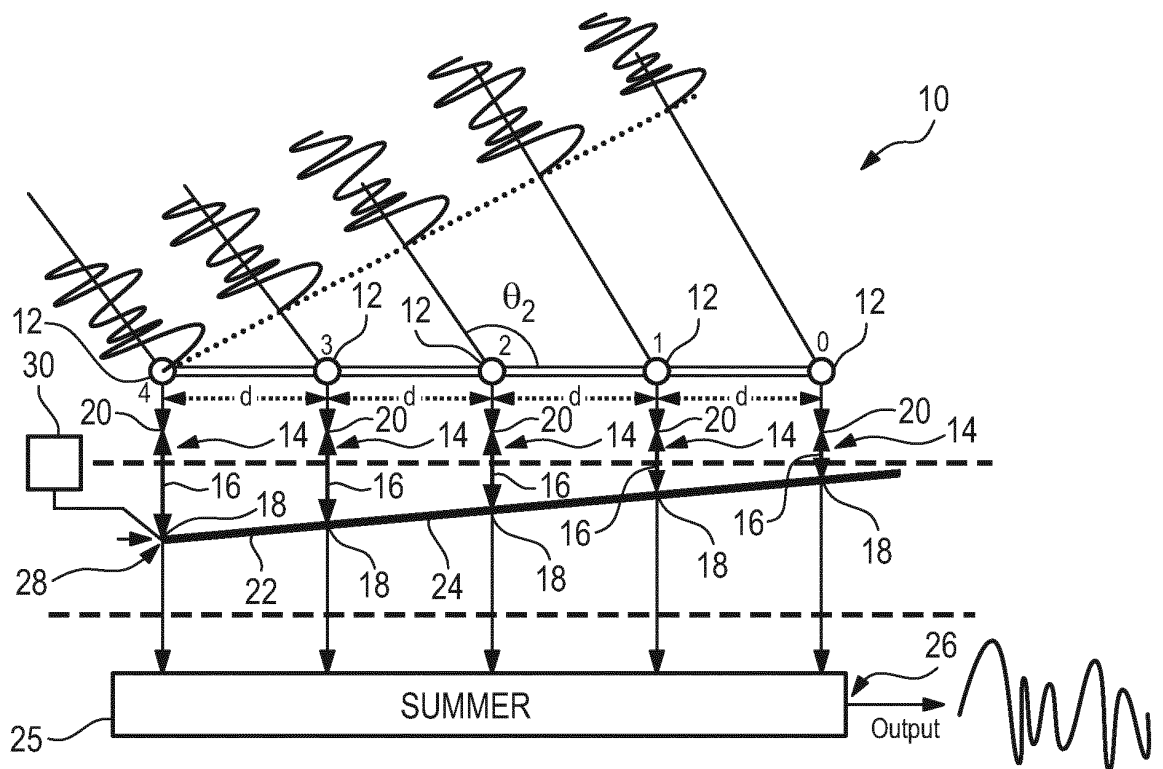


Fig. 4

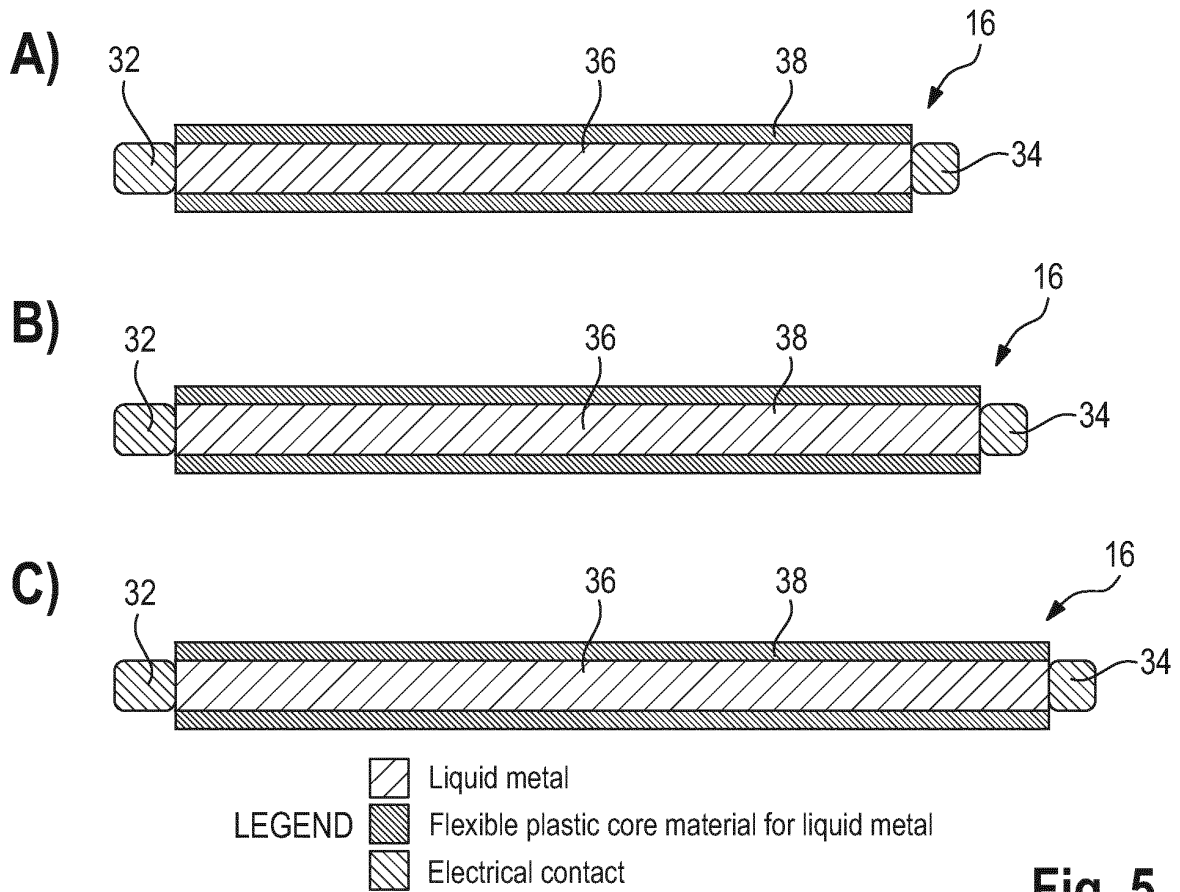


Fig. 5

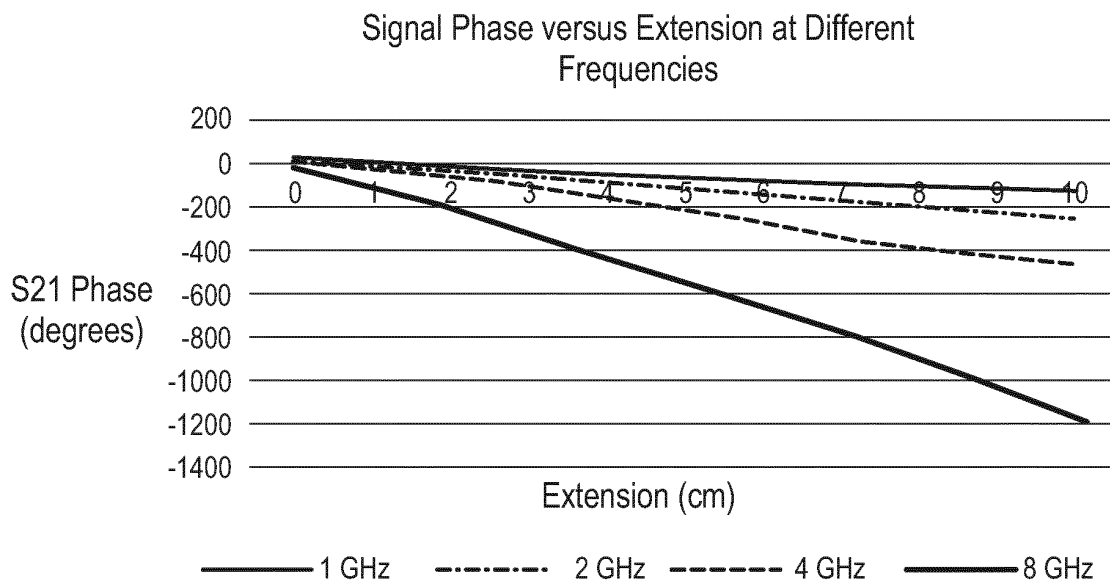


Fig. 6



EUROPEAN SEARCH REPORT

Application Number

EP 22 19 6851

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DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
Y	HENSLEY DAVID ET AL: "A Stretchable Liquid Metal Antenna Array", 2021 IEEE INTERNATIONAL SYMPOSIUM ON ANTENNAS AND PROPAGATION AND USNC-URSI RADIO SCIENCE MEETING (APS/URSI), IEEE, 4 December 2021 (2021-12-04), pages 1777-1778, XP034084941, DOI: 10.1109/APS/URSI47566.2021.9704298 [retrieved on 2022-02-03] * sections I, II, and V * * figure 1 * * table 1 *	1-15	INV. H01Q3/32 ADD. H01P1/18
Y	HAYES GERARD J. ET AL: "Microfluidic coaxial transmission line and phase shifter", MICROWAVE AND OPTICAL TECHNOLOGY LETTERS, [Online] vol. 56, no. 6, 1 June 2014 (2014-06-01), pages 1459-1462, XP093027984, US ISSN: 0895-2477, DOI: 10.1002/mop.28327 Retrieved from the Internet: URL:https://api.wiley.com/onlinelibrary/tdm/v1/articles/10.1002%2Fmop.28327> * the whole document *	1-15	TECHNICAL FIELDS SEARCHED (IPC) H01P H01Q
Y	HENSLEY DAVID M ET AL: "A Stretchable Liquid Metal Coaxial Phase Shifter", IEEE OPEN JOURNAL OF ANTENNAS AND PROPAGATION, IEEE, vol. 2, 2 March 2021 (2021-03-02), pages 370-374, XP011842190, DOI: 10.1109/OJAP.2021.3063289 [retrieved on 2021-03-11] * the whole document *	1-15	
The present search report has been drawn up for all claims			

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Place of search

Date of completion of the search

Examiner

Munich

3 March 2023

Patrovsky, Andreas

CATEGORY OF CITED DOCUMENTS

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