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(54) **TUNEABLE BANDPASS FILTER**

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(57) **ABSTRACT**

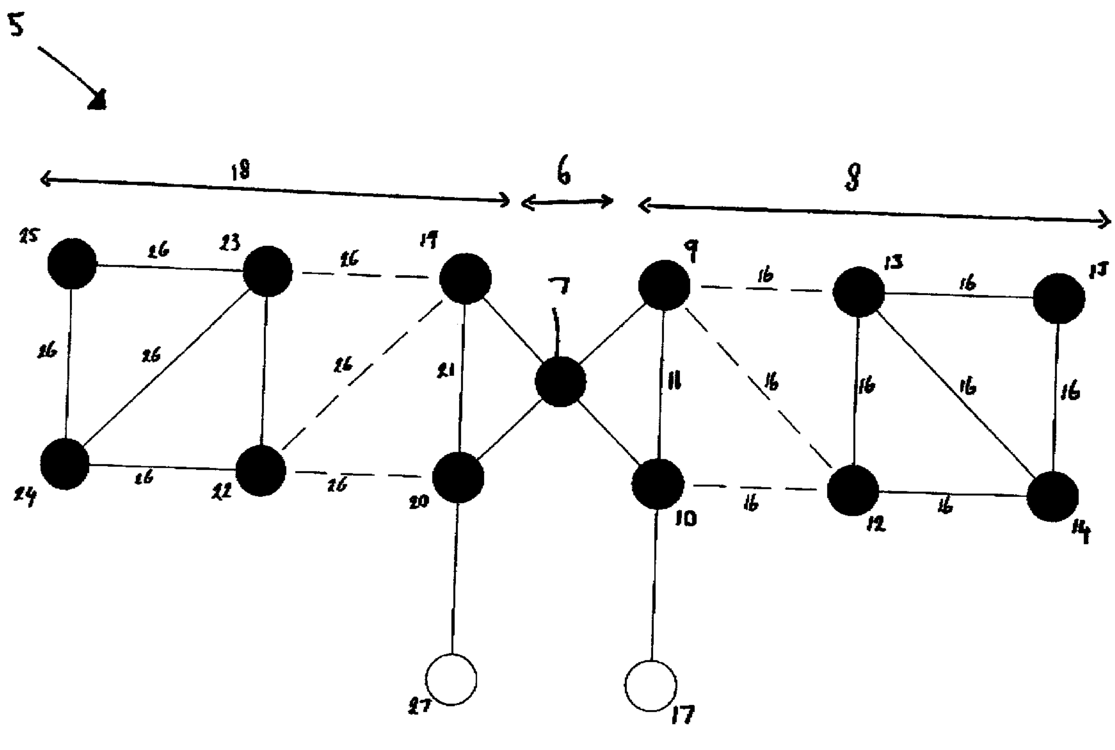
A tuneable bandpass filter comprising a plurality of coupled resonators, the filter comprising

a common structure comprising at least one common coupling or one common resonator;

an upper loop comprising first and second end resonators coupled together by a signal path, the loop further comprising at least one further signal path extending between end resonators, the further signal path comprising at least one further resonator, the end resonators being coupled to the common structure;

a lower loop comprising first and second end resonators coupled together by a signal path, the loop further comprising at least one further signal path extending between end resonators, the further signal path comprising at least one further resonator, the end resonators being coupled to the common structure;

the resonators being coupled together such that the bandpass filter can be divided into a low pass sub filter and a high pass sub filter, one of the sub filters being arranged to receive the output of the other.



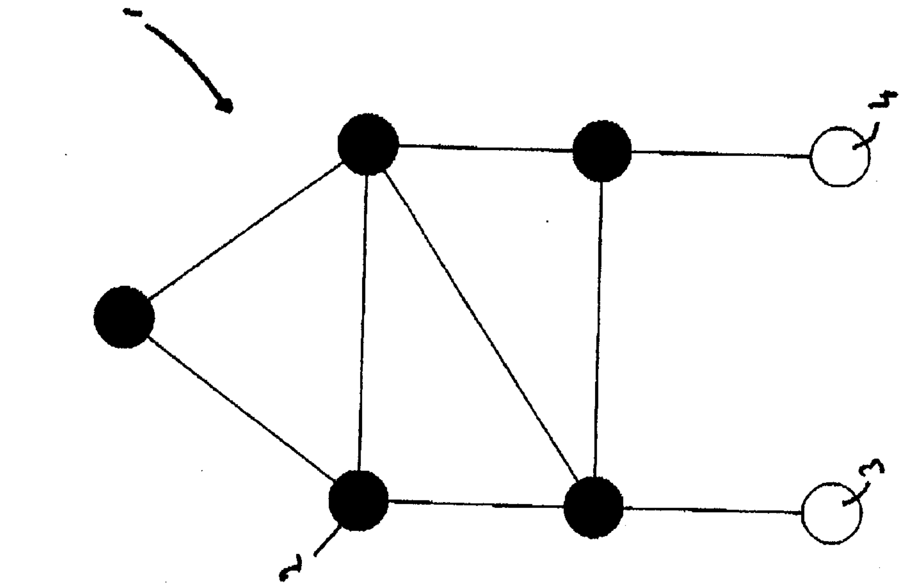


Figure 1b

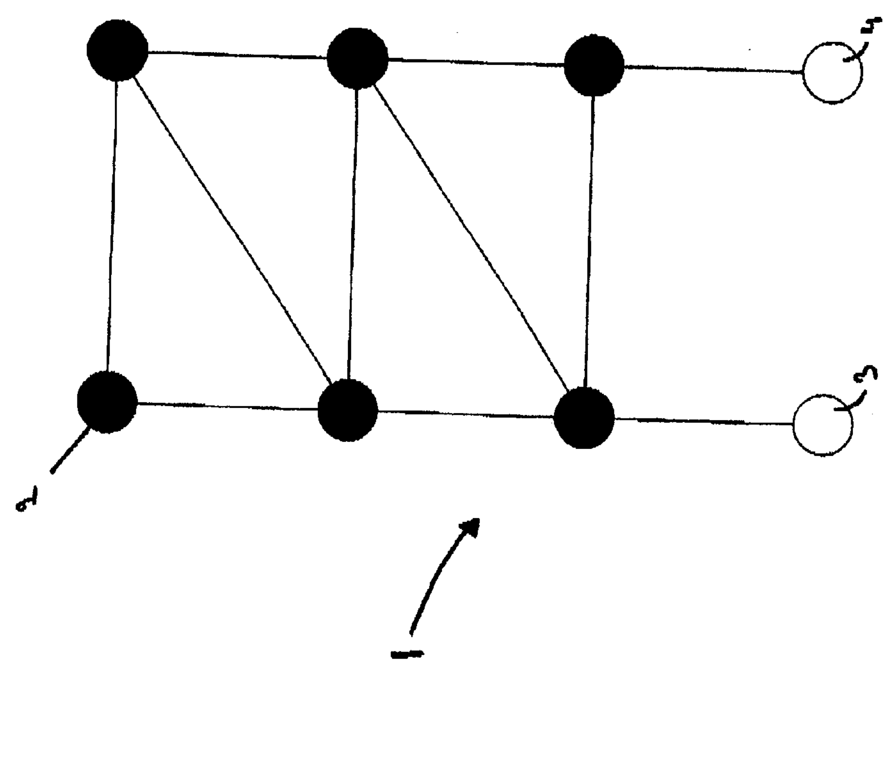


Figure 1a

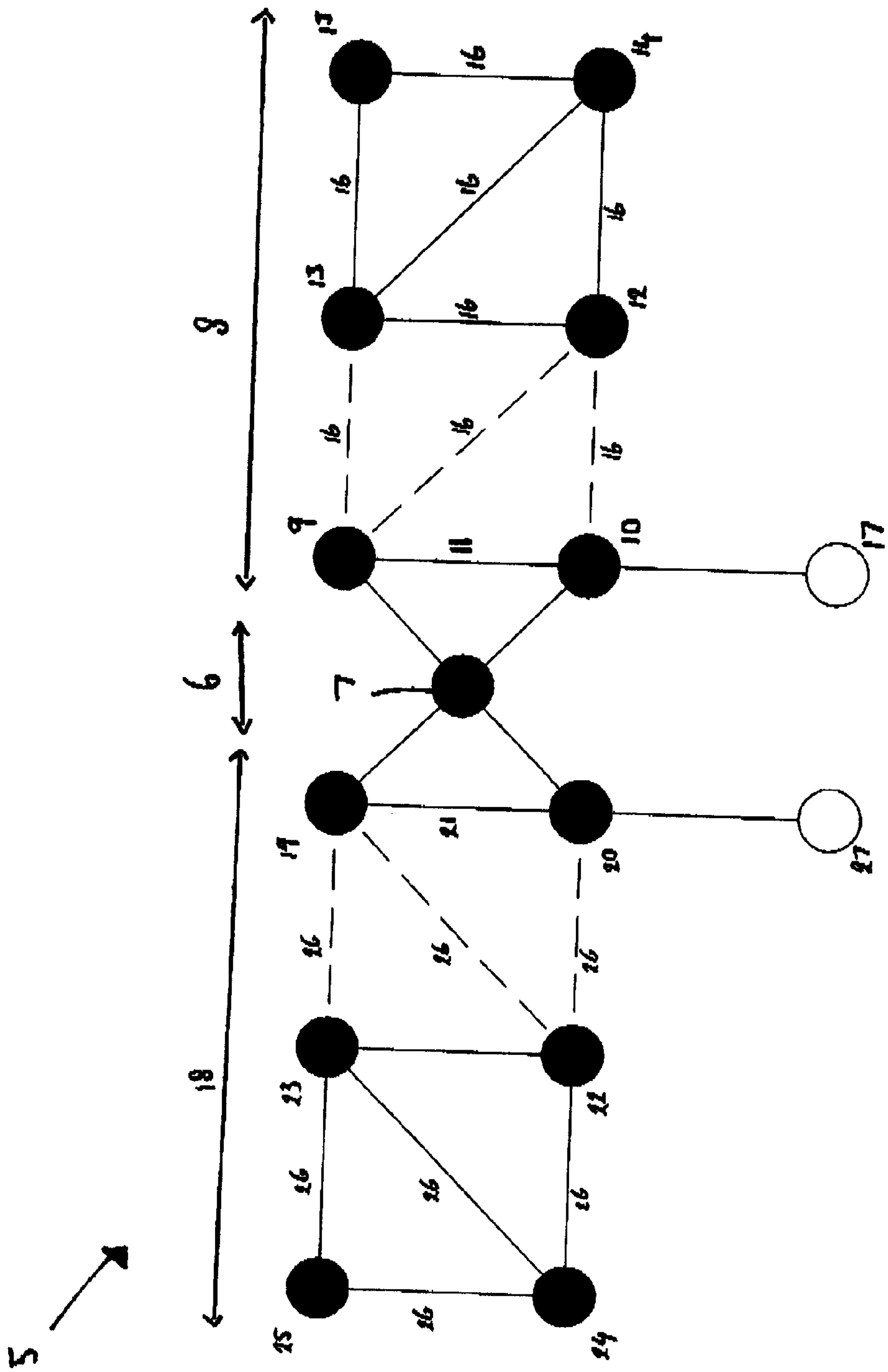


Figure 2

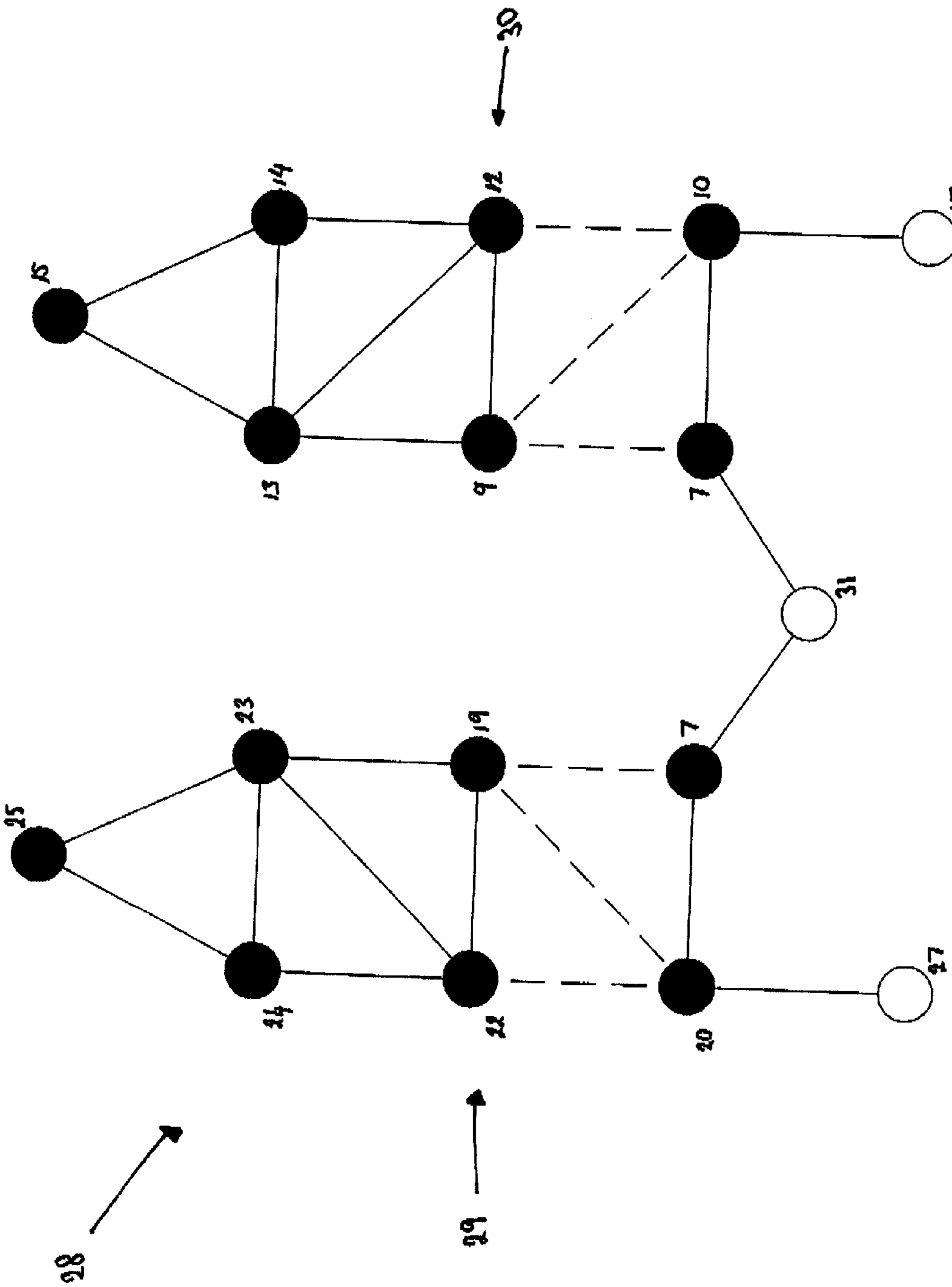


Figure 3

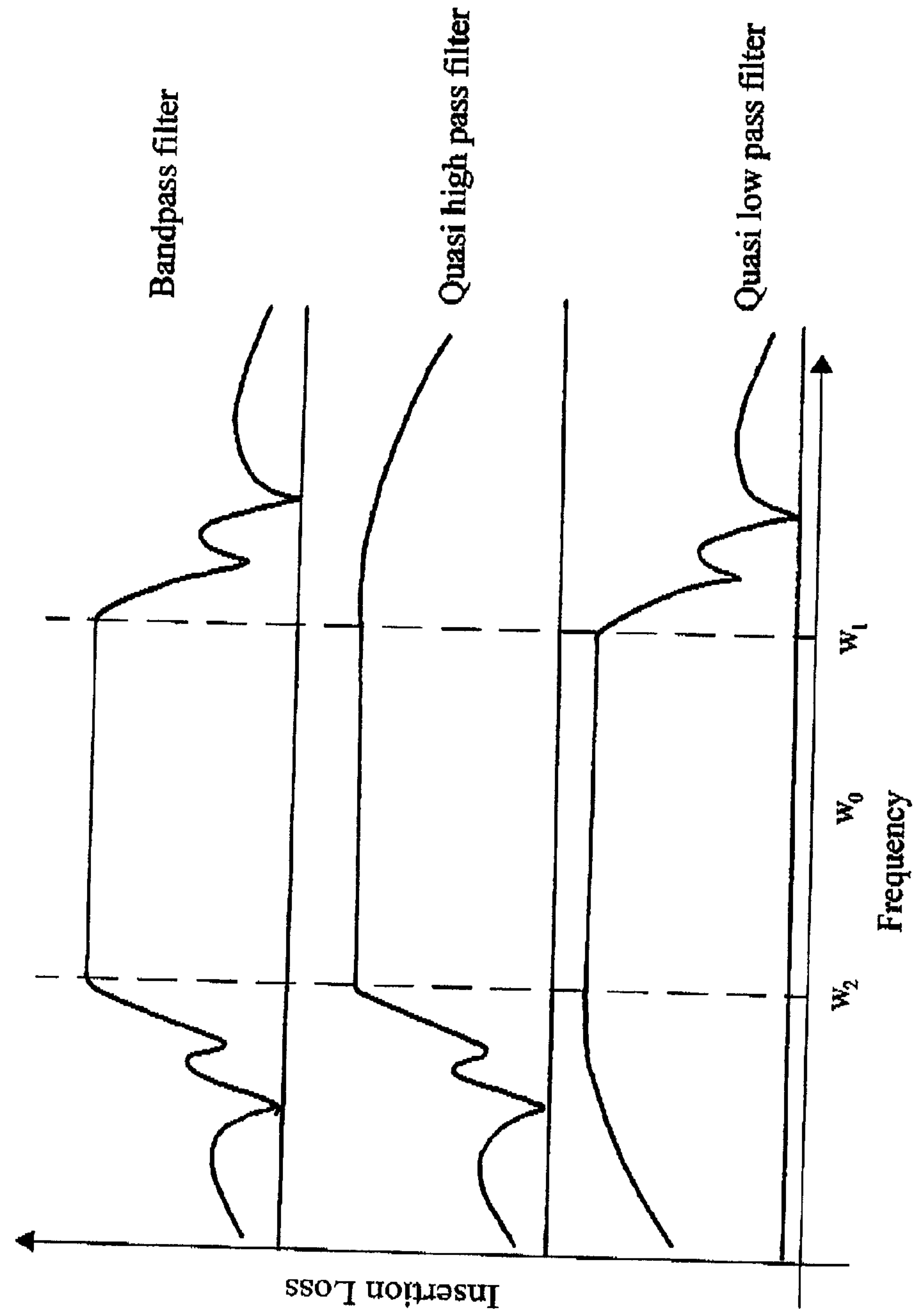

Bandpass filter
Quasi high pass filter
Quasi low pass filter
Insertion Loss
w_1
w_0
w_2
Frequency

Figure 4

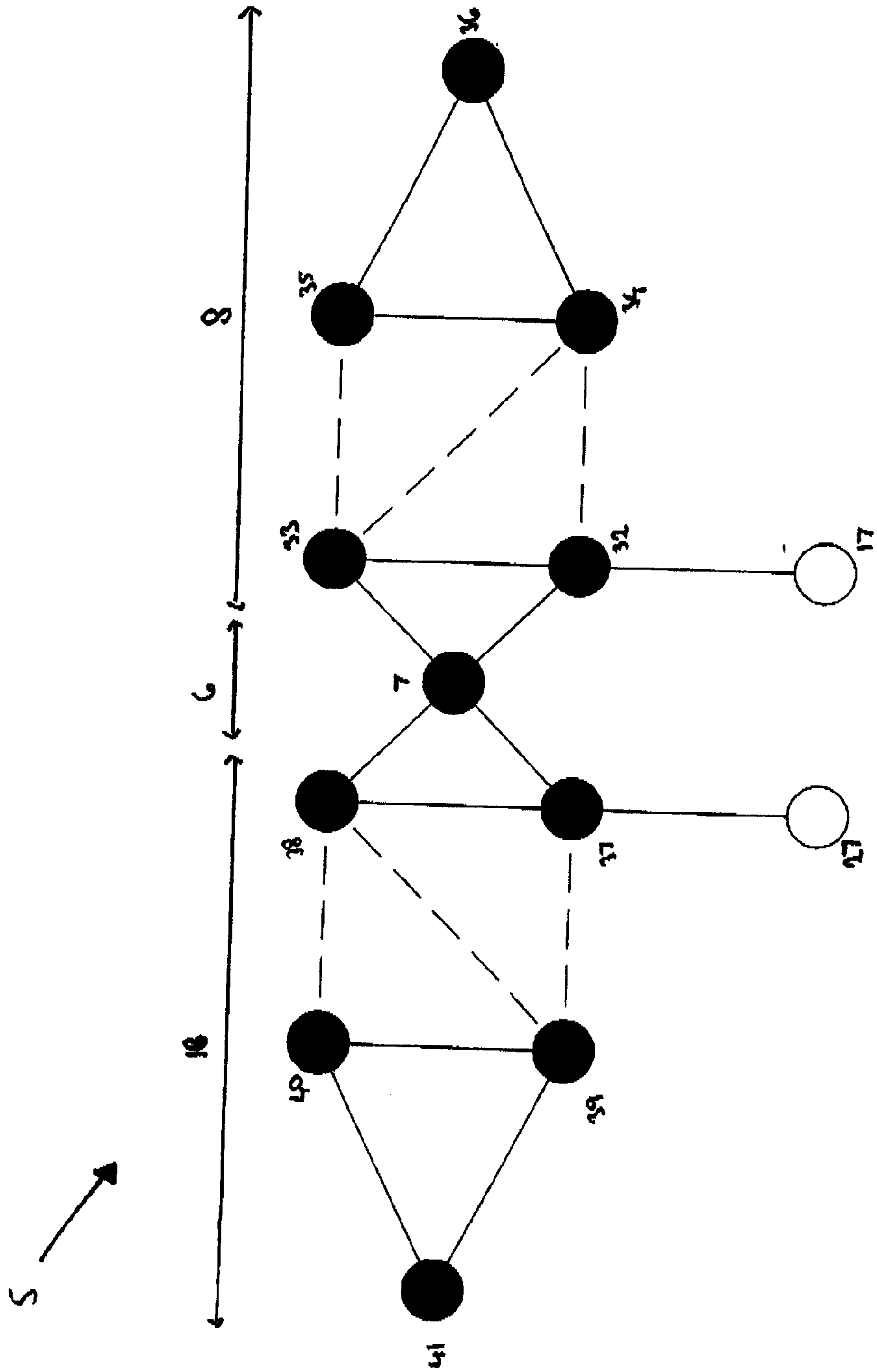


Figure 5

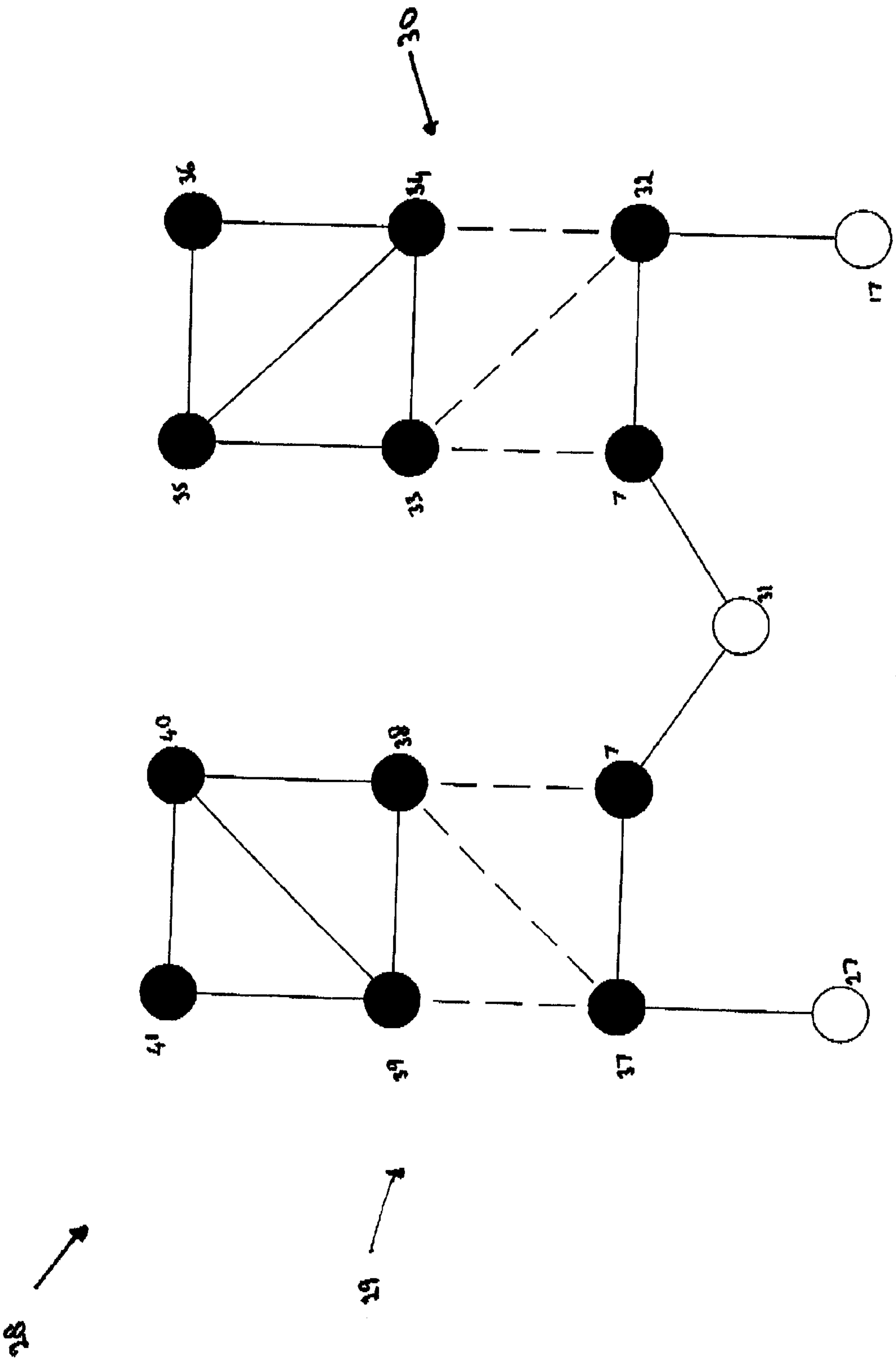


Figure 6

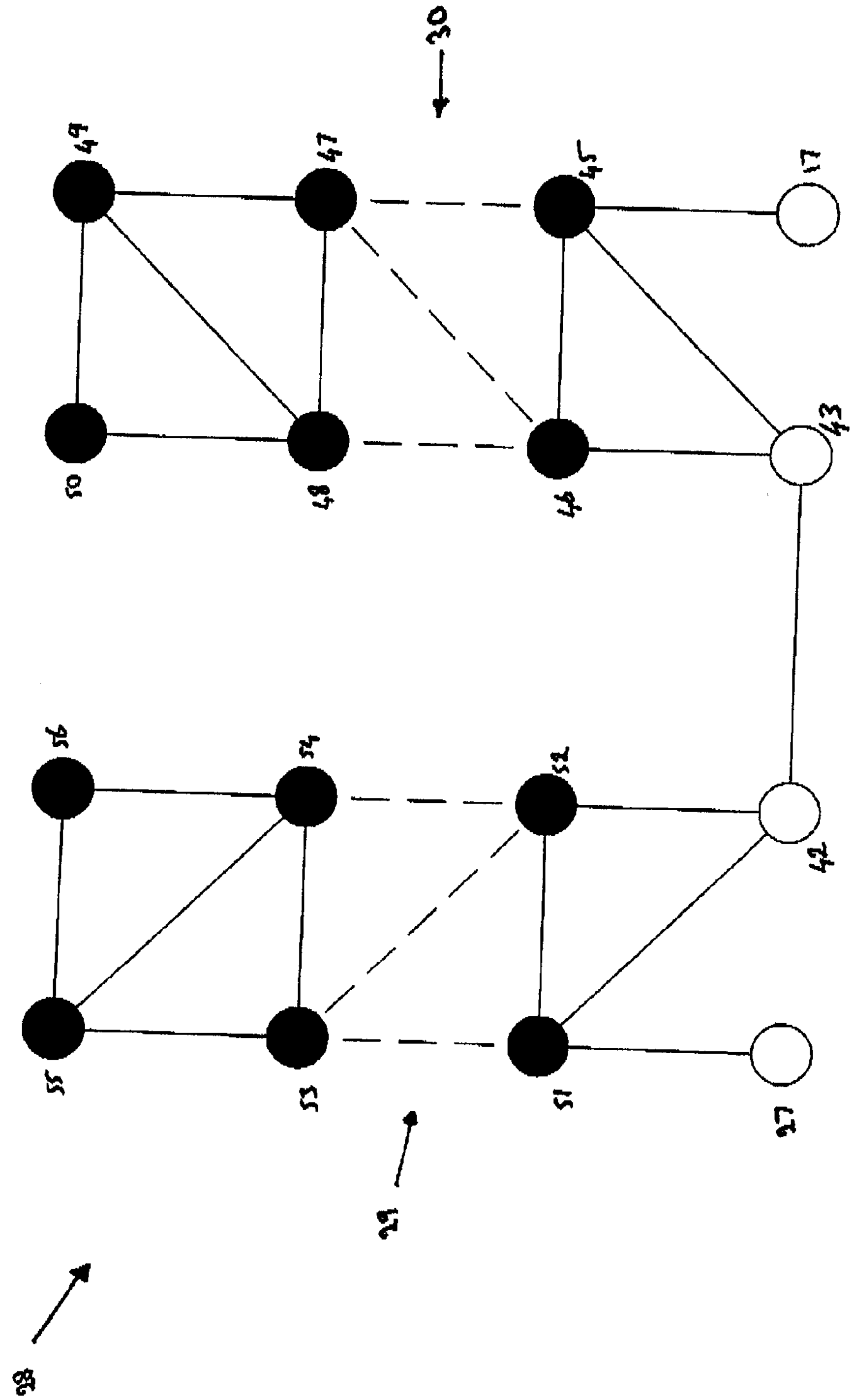


Figure 7

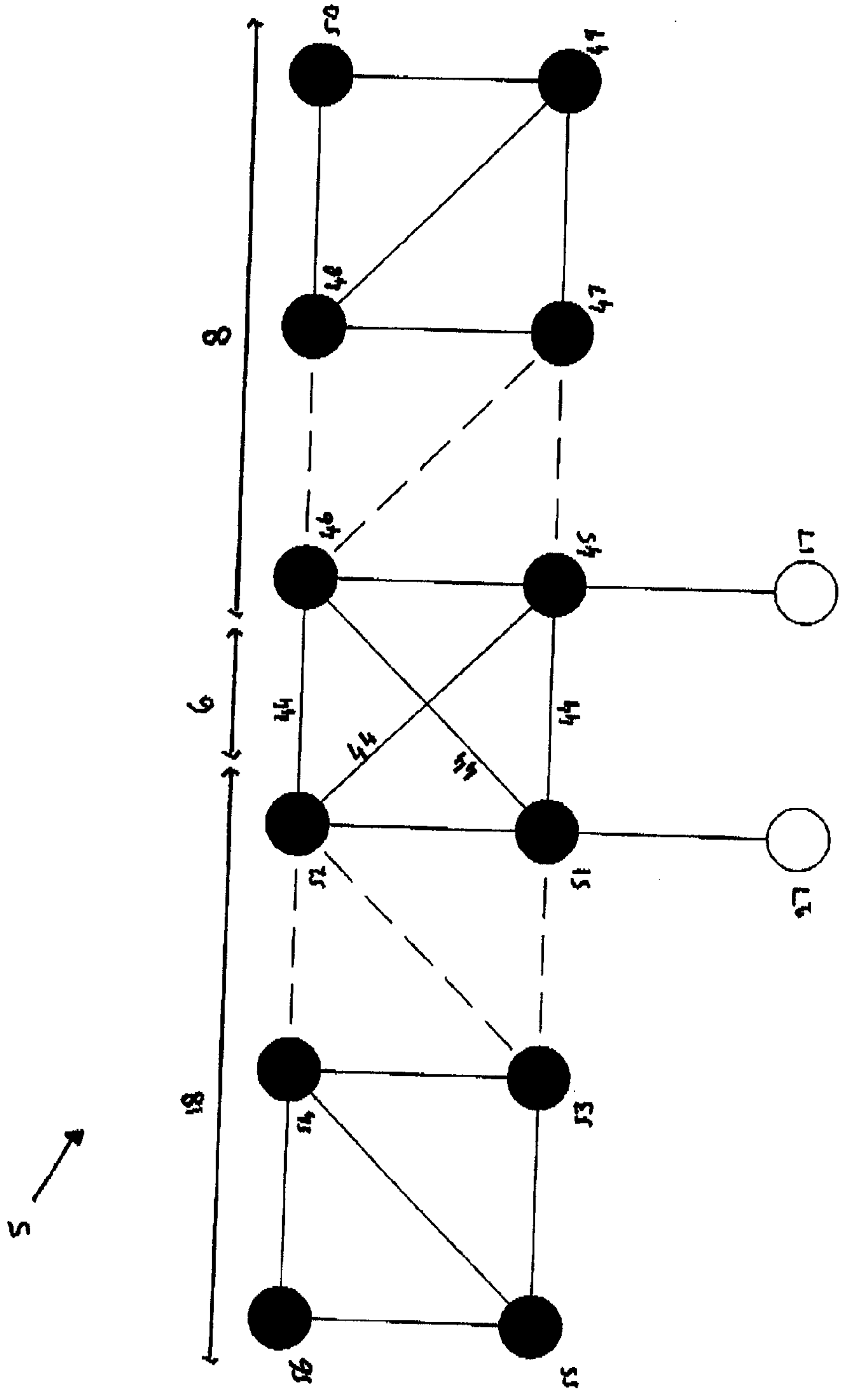


Figure 8

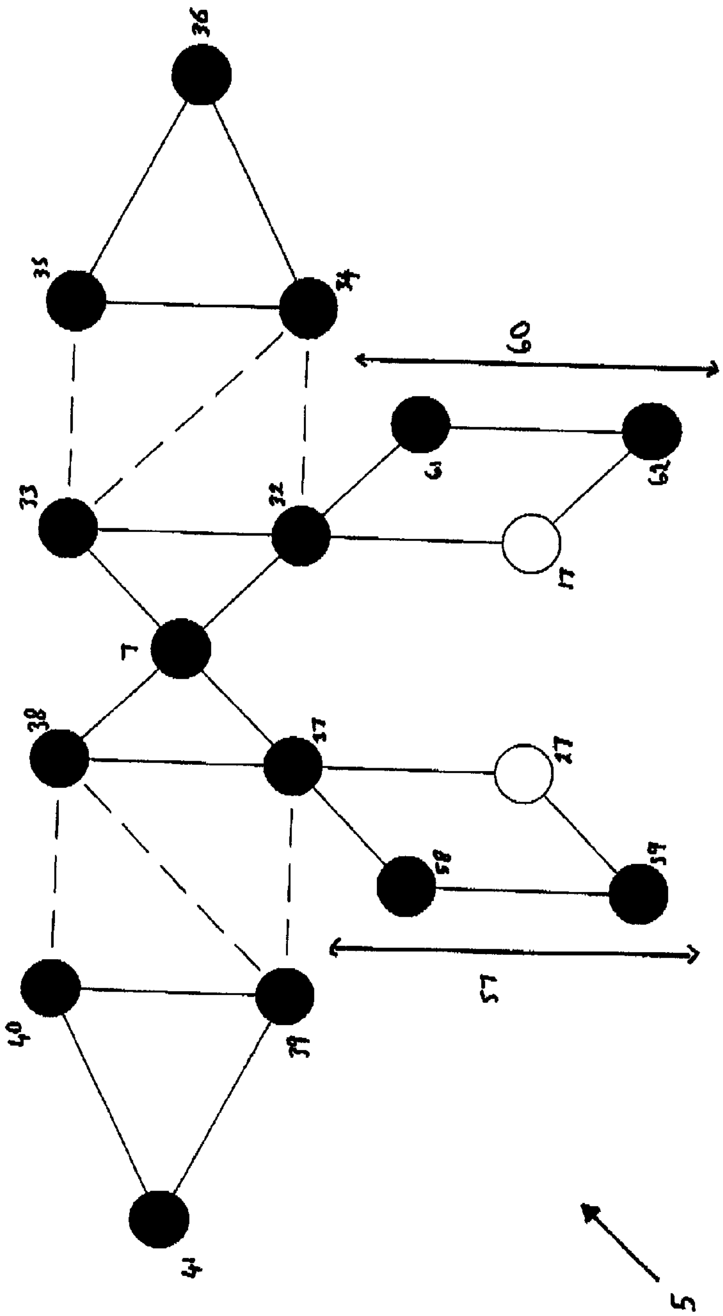


Figure 9

TUNEABLE BANDPASS FILTER

[0001] The present invention relates to a tuneable bandpass filter. More particularly, but not exclusively, the present invention relates to a tuneable bandpass filter comprising a plurality of coupled resonators, the resonators being arranged in first and second loops, each connected to a common structure, the resonators being arranged such that the filter can be de-composed into low pass and high pass sub filters, one sub filter being arranged to receive the output of the other.

[0002] There are many requirements which require a filter constructed from coupled resonant structures to be tuned with control over operating bandwidth and frequency whilst retaining fixed absolute rejection requirements relative to the band edges. Using known synthesis and implementation methods tuning band pass filters with variable frequency and bandwidth would require tuning of both the resonant frequency of the resonators and the coupling between the resonators and would only meet relative rejection requirements. This results in filters which are complex to implement.

[0003] The tuneable bandpass filter according to the invention seeks to overcome this problem.

[0004] Accordingly, the present invention provides a tuneable bandpass filter comprising a plurality of coupled resonators, the filter comprising

- **[0005]** a common structure comprising at least one common coupling or one common resonator;
- **[0006]** an upper loop comprising first and second end resonators coupled together by a signal path, the loop further comprising at least one further signal path extending between end resonators, the further signal path comprising at least one further resonator, the end resonators being coupled to the common structure;
- **[0007]** a lower loop comprising first and second end resonators coupled together by a signal path, the loop further comprising at least one further signal path extending between end resonators, the further signal path comprising at least one further resonator, the end resonators being coupled to the common structure;
- **[0008]** the resonators being coupled together such that the bandpass filter can be divided into a low pass sub filter and a high pass sub filter, one of the sub filters being arranged to receive the output of the other.

[0009] The tuneable bandpass filter according to the invention has a bandwidth and centre frequency of bandpass response which can be tuned by tuning the resonators only, without the need to adjust the coupling between resonators.

[0010] The common structure can comprise a single common resonator, the end resonators of the upper and lower loops being connected to the common resonator.

[0011] The low pass sub filter can comprise the common resonator and the resonators of the lower loop.

[0012] The high pass sub filter can comprise the common resonator and the resonators of the upper loop.

[0013] Alternatively, the common structure can comprise a plurality of common couplings coupled between the upper and lower loops.

[0014] The common couplings can be arranged such that each end resonator of a loop is coupled to both end resonators of the other loop.

[0015] The upper loop can comprise an even number of resonators.

[0016] Alternatively, the upper loop can comprise an odd number of resonators.

[0017] The lower loop can comprise an even number of resonators.

[0018] Alternatively, the lower loop can comprise an odd number of resonators. At least one of the upper loop and lower loop can comprise a plurality of resonators coupled together.

[0019] At least one of the loops can comprise a plurality of resonators coupled together in cascade such that there are a plurality of signal paths between end resonators. At least some of the resonators of the at least one loop can be coupled together in a cross coupled ladder configuration.

[0020] At least some of the resonators in the cross coupled ladder configuration can further comprise at least one diagonal cross coupling to a resonator on an adjacent cross coupled ladder rung.

[0021] The filter can further comprise a non-resonant input circuit node coupled to an end resonator of one of the loops.

[0022] The filter can further comprise a group delay equalisation network further coupled between input circuit node and end resonator connected thereto.

[0023] The filter can further comprise an output circuit node coupled to an end resonator of the other loop.

[0024] The filter can further comprise a group delay equalisation network connected between output circuit node and end resonator connected thereto.

[0025] The present invention will now be described by way of example only, and not in any limitative sense with reference to the accompanying drawings in which

[0026] FIGS. **1**(*a*) and **1**(*b*) show known coupled resonator bandpass filters having an even and odd number of coupled resonators respectively;

[0027] FIG. **2** shows a first embodiment of a tuneable bandpass filter according to the invention;

[0028] FIG. **3** shows an equivalent circuit for the filter of FIG. **2**;

[0029] FIG. **4** shows a plot of insertion loss against frequency for the filter of FIG. **2**;

[0030] FIG. **5** shows a second embodiment of a tuneable bandpass filter according to the invention;

[0031] FIG. **6** shows an equivalent circuit for the filter of FIG. **5**;

[0032] FIG. **7** shows an equivalent circuit for a further embodiment of a filter according to the invention;

[0033] FIG. **8** shows a filter according to the invention having the equivalent circuit of FIG. **7**; and,

[0034] FIG. **9** shows a further embodiment of a filter according to the invention.

[0035] Bandpass filters at RF and microwave frequencies are commonly realised as networks of resonant circuits with coupling between them. Shown in FIGS. **1**(*a*) and **1**(*b*) are such known bandpass filters **1**. The filters **1** each comprise a plurality of resonators **2**. The resonators **2** are coupled together in cross coupled ladder configurations as shown. Input and output connections to the bandpass filters **1** are through non-resonant circuit nodes **3**,**4**.

[0036] The synthesis of these networks to generate arbitrary asymmetric responses is known. The coupling elements shown as diagonal lines can be generated in either direction.

[0037] The centre of the passband of the filter **1** is determined by the resonant frequency of the resonators **2** and the general shape of the response is determined by the ratios and topology of the couplings. Changing the centre frequency of the filter **1** can be achieved by changing only the resonator frequency of the resonators **2**. Changing the relative bandwidth of a filter **1** requires the modification of the coupling between the resonators **2** and the frequencies of the resonators **2**. Such filters **1** tend to be complex both to manufacture and to use and in general will only retain a relative selectivity requirement if the couplings are not modified.

[0038] An infinite number of variants of the structures in FIG. **1** can be achieved by applying rotational transformations on the coupling matrix of the filter **1**.

[0039] Shown in FIG. **2** is a tuneable bandpass filter **5** according to the invention. The filter **5** comprises a common structure **6** comprising a single common resonator **7**. The filter **5** comprises an upper loop **8** comprising first and second end resonators **9**,**10** coupled together by a signal path **11**. Each end resonator **9**,**10** is further coupled to the common resonator **7**. The upper loop **8** further comprises a plurality of further resonators **12**-**15** coupled along a plurality of signal paths **16** between the end resonators **9**,**10**. The resonators **9**,**10**, **12**-**15** of the upper loop **8** are coupled in a cross coupled ladder configuration. The diagonal couplings **16** between the resonators on different rungs can be generated in either direction. The dotted lines show repeated units. In this embodiment the upper loop **8** comprises six resonators although other embodiments with 8, 10, 12 etc resonators are also possible. Coupled to one of the end resonators **10** of the upper loop **8** is a non-resonant output signal node **17**.

[0040] The filter **5** also comprises a lower loop **18** comprising first and second end resonators **19**,**20** coupled together by a signal path **21**. Each end resonator **19**,**20** is coupled to the common resonator **7**. The lower loop **18** further comprises a plurality of further resonators **22**-**25** coupled along a plurality of signal paths **26** between end resonators **19**,**20**. The topology of the lower loop **18** is such that, in this embodiment, the filter **5** has complex conjugate symmetry about the common resonator **7**. Coupled to one of the end resonators **20** of the lower loop **18** is a non-resonant input signal node **27**.

[0041] Shown in FIG. **3** is an equivalent circuit **28** for the tuneable bandpass filter **5** of FIG. **2**. In the equivalent circuit **28** the tuneable bandpass filter **5** is split into two sub filters **29**,**30** connected together at a non-resonant node **31**. Like resonators in the tuneable bandpass filter **5** and its equivalent circuit **28** are referenced by like reference numerals. One of the sub-filters **29** comprises a low pass sub filter **29** having a low pass band edge at frequency w_1. The other sub filter **30** comprises a high pass sub filter **30** having a high pass band edge at frequency w_2. The equivalent circuit **28** comprises one more resonant node than the tuneable bandpass filter **5**. This is because the common resonator **7** is formed from a merging of the first resonator **7** of the low pass sub filter **29** with the first resonator **7** of the high pass sub filter **30**.

[0042] The insertion loss of the tuneable band pass filter **5** is a combination of the insertion losses of the low pass and high pass sub filters **29**,**30** of the equivalent circuit **28**. FIG. **4** shows the insertion loss of the tuneable bandpass filter **5** and also the insertion loss of the sub filters **29**,**30** of its equivalent circuit **28**, taking into account the interaction of the two. As the band edge of the low pass sub filter **29** is at a higher frequency than the band edge of the high pass sub filter **30**, the combined insertion loss comprises a bandpass region centred about w_0 having edges at w_1 and w_2 respectively.

[0043] The low pass and high pass sub filters **29**,**30** can be altered substantially independently of each other. Accordingly, in order to change the lower band edge one adjusts the resonant frequencies of the resonators **7**,**9**,**10**,**12**,**13**,**14**,**15** of the tuneable bandpass filter **5** which comprise the high pass sub filter **30** of its equivalent circuit **28**. In order to change the upper band edge one adjusts the resonant frequencies of the resonators of the tuneable bandpass filter **5** comprising the low pass sub filter **29** of the equivalent circuit **28**. By adjusting the upper and lower band edges one can adjust the centre and width of the bandpass region of the tuneable bandpass filter **5** purely by adjusting the resonant frequencies of the resonators and without the need to adjust the coupling between them. This significantly reduces the complexity of the tuneable bandpass filter **5** and increases its ease of use compared to known bandpass filters and preserves the same absolute selectivity.

[0044] The tuneable bandpass filter **5** of this embodiment normally has a high degree of symmetry. Because of the symmetry of the filter **5** the common resonator **7** is normally tuned to the centre of the filter passband. In order to change the bandwidth (constant centre frequency) one tunes all the resonators except the common resonator **7**.

[0045] In an alternative embodiment of the invention (not shown) the tuneable bandpass filter **5** is asymmetric and can be decomposed into a low pass sub filter **29** of degree n_L and high pass sub filter **30** of degree n_H. For such a filter **5** one must tune n_L resonators to move the lower edge and n_H resonators to move the upper edge (including the common resonator **7**). To move the centre frequency of the response all resonators must be altered.

[0046] Shown in FIG. **5** is a further embodiment of a tuneable bandpass filter **5** according to the invention. In this embodiment the upper and lower loops **8**,**18** comprise an odd number of resonators. In the equivalent circuit **28** shown in FIG. **6** the two sub filters **29**,**30** have an even number of resonators. Again, the two sub filters **29**,**30** are low pass **29** and high pass **30** sub filters respectively.

[0047] In all of the above embodiments of the invention the low pass and high pass sub filters **29**,**30** of the equivalent circuits **28** have two transmission zeros at infinity. However, this is not necessary. Shown in FIG. **7** is the equivalent circuit **28** for a tuneable filter **5** wherein the low pass and high pass sub filters **29**,**30** have only one transmission zero at infinity. Moving one of the transmission zeros from infinity results in additional flexibility when meeting design specifications. The low and high pass sub filters **29**,**30** are now connected together by two non-resonant nodes **42**,**43**.

[0048] The topology of the tuneable bandpass filter **5** is shown in FIG. **8**. As with the previous embodiments the filter **5** comprises upper and lower loops **8**,**18** each comprising a plurality of resonators. The common structure **6** however is more complex. In this embodiment the common structure **6** comprises a plurality of common couplings **44** arranged to fully couple the end resonators **45**,**46**,**51**,**52** of the upper and lower loops **8**,**18**. Each end resonator **45**,**46**,**51**,**52** of one loop **8**,**18** is coupled to both end resonators **45**,**46**,**51**,**52** of the other loop **8**,**18**.

[0049] The tuneable bandpass filter **5** of FIG. **8** retains the same basic properties of the other tuneable bandpass filters **5** according to the invention. In particular independent tuning of the bandpass filter bandwidth and centre frequency is achievable by tuning the relevant resonators. No tuning of the coupling between resonators is required to tune either centre frequency or bandwidth.

[0050] Shown in FIG. **9** is a further embodiment of a tuneable bandpass filter **5** according to the invention. An ideal filter would pass signals in a desired band whilst attenuating all unwanted signals with only a constant change in amplitude and constant time delay to the desired signals. If different frequency components of a complex signal arrive at different times the signal will be distorted. The requirement for a constant time delay equates to a need for a constant group delay. The absolute level of the delay is usually not important, what is important is the variation of the delay over the signal bandwidth.

[0051] The embodiment of the filter **5** of FIG. **9** further comprises a compensating group delay equalisation network **57** coupled between the input non-resonant node **27** and resonator **37** connected to the input node **27**, in addition to the direct coupling between the two. The compensating group delay equalisation network **57** comprises a plurality of resonators **58**,**59** coupled together in series. A further compensating group delay equalisation network **60** is coupled between the output non-resonant node **17** and resonator **32** coupled to the output node **17**. Again, this comprises a plurality of resonators **61**,**62** coupled together in series. Again, this is in parallel to the direct coupling between the output node **17** and resonator **32**. The responses of the compensating group delay equalisation networks **57**,**60** are offset from the centre frequency of the desired bandpass response so that each compensating network **57**,**60** affects one half of the band more than the other. The group delay peak of the compensating networks **57**,**60** occurs at the nominal centre frequency of the compensator design. To compensate the group delay dip in the middle of the bandpass response, the nominal centre frequency of the compensators occurs within the passband of the bandpass response. In order to apply the correct compensation to the response they must be symmetrically spaced about the centre frequency of the bandpass response for symmetrical amplitude selectivity requirements.

[0052] The compensating group delay equalisation networks **57**,**60** can be tuned. The compensating group delay equalisation networks **57**, **60** are adapted to track the tuning of the filter **5** by synchronising the frequencies, with the centre frequencies correctly offset, of the compensating group delay equalisation networks **57**,**60** relative to the overlap of the low pass and high pass sub filters **29**,**30** of the tuneable bandpass filter **5**.

[0053] If the centre frequency of the compensating group delay equalisation networks **57**,**60** relative to the overlap of the low pass and high pass sub filters **29**,**30** is altered the amount of compensation and the relative position of the group delay ripples can be altered.

[0054] The compensating group delay equalisation networks **57**,**60** can be used to reduce the group delay variation for all tuneable bandwidths. In addition to reducing the group delay variation the variation in insertion loss in the compensation networks **57**,**60** also reduces the insertion loss variation across the passband, although this comes at the cost of increased minimum insertion loss.

[0055] The low pass sub filters **29** of the equivalent circuits **28** above are essentially bandpass filters with a performance tailored to favour stopband rejection above the passband of the tuneable bandpass filter **5** with little regard to performance below the passband of the tuneable bandpass filter **5**. Such filters **29** are often termed 'quasi' low pass filters.

[0056] Similarly, the high pass sub filters **30** of the equivalent circuits **28** are essentially bandpass filters with a performance tailored to favour stopband rejection below the passband of the tuneable bandpass filter **5** with little regard to performance above the passband of the tuneable bandpass filter **5**. Such filters **30** are often termed 'quasi' high pass filters.

[0057] The tuneable bandpass filter **5** according to the invention is typically used with resonators which resonate at microwave frequencies, producing a passband in the microwave region. Typically the resonators comprise cavity resonators (not shown) which are tuned by displacing a tuning member within the cavity. Two tuneable cavity resonators are typically coupled by means of an aperture which extends through the common wall of the two cavities.

[0058] In all of the above embodiments the resonators of the tuneable bandpass filter are connected together in arrangements such that the filter can be considered to be a quasi high pass sub filter and a quasi low pass sub filter connected together with one receiving the output of the other. In these embodiments the output of one sub-filter is connected to the input of the other by a number of non-resonant nodes, the number of nodes depending upon the order of the sub-filters.

1. A tuneable bandpass filter comprising a plurality of coupled resonators, the filter comprising:

a common structure comprising at least one common coupling or one common resonator;

an upper loop comprising first and second end resonators coupled together by a signal path, the upper loop further comprising at least one further signal path extending between the end resonators of the upper loop, the further signal path of the upper loop comprising at least one further resonator, the end resonators of the upper loop being coupled to the common structure;

a lower loop comprising first and second end resonators coupled together by a signal path, the lower loop further comprising at least one further signal path extending between the end resonators of the lower loop, the further signal path of the lower loop comprising at least one further resonator, the end resonators of the lower loop being coupled to the common structure;

the resonators being coupled together such that the bandpass filter can be divided into a low pass sub filter and a high pass sub filter, one of the sub filters being arranged to receive the output of the other.

2. A tuneable bandpass filter as claimed in claim **1**, wherein the common structure comprises a single common resonator, the end resonators of the upper and lower loops being connected to the common resonator.

3. A tuneable bandpass filter as claimed in claim **2**, wherein the low pass sub filter comprises the common resonator and the resonators of the lower loop.

4. A tuneable bandpass filter as claimed in claim **2**, wherein the high pass sub filter comprises the common resonator and the resonators of the upper loop.

5. A tuneable bandpass filter as claimed in claim **1**, wherein the common structure comprises a plurality of common couplings coupled between the upper and lower loops.

6. A tuneable bandpass filter as claimed in claim **5**, wherein the common couplings are arranged such that each end resonator of a loop is coupled to both end resonators of the other loop.

7. A tuneable bandpass filter as claimed in claim **1**, wherein the upper loop comprises an even number of resonators.

8. A tuneable bandpass filter as claimed in claim **1**, wherein the upper loop comprises an odd number of resonators.

9. A tuneable bandpass filter as claimed in claim **1**, wherein the lower loop comprises an even number of resonators.

10. A tuneable bandpass filter as claimed in claim **1**, wherein the lower loop comprises an odd number of resonators.

11. A tuneable bandpass filter a claimed in claim **1**, wherein at least one of the upper loop and lower loop comprises a plurality of resonators coupled together.

12. A tuneable bandpass filter as claimed in claim **11**, wherein at least one of the loops comprises a plurality of resonators coupled together in cascade such that there are a plurality of signal paths between end resonators.

13. A tuneable bandpass filter as claimed in claim **12**, wherein at least some of the resonators of the at least one loop are coupled together in a cross coupled ladder configuration.

14. A tuneable bandpass filter as claimed in claim **13**, wherein at least some of the resonators in the cross coupled ladder configuration further comprise at least one diagonal cross coupling to a resonator on an adjacent cross coupled ladder rung.

15. A tuneable bandpass filter as claimed in claim **1**, further comprising a non-resonant input circuit node coupled to an end resonator of one of the loops.

16. A tuneable bandpass filter as claimed in claim **15**, further comprising a group delay equalisation network further coupled between input circuit node and end resonator connected thereto.

17. A tuneable bandpass filter as claimed in claim **15**, further comprising an output circuit node coupled to an end resonator of the other loop.

18. A tuneable bandpass filter as claimed in claim **17**, further comprising a group delay equalisation network connected between output circuit node and end resonator connected thereto.

19.-**20**. (canceled)

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