United States Patent [19]

Rizzi

[11] **3,778,733**

[45] **Dec. 11, 1973**

[54] **FILTER-TYPE DIGITAL DIODE PHASE SHIFTER**

[75] Inventor: **Peter A. Rizzi**, Dedham, Mass.

[73] Assignee: **Alpha Industries, Inc.**, Woburn, Mass.

[22] Filed: **May 8, 1972**

[21] Appl. No.: **251,116**

[52] **U.S. Cl.** ..... **333/31 R**, 333/73 C, 333/97 S

[51] **Int. Cl.** **H01p 1/18**

[58] **Field of Search** ..... 333/31 R, 70 R, 73 R, 333/73 C, 73 S; 307/256, 259

[56] **References Cited**

UNITED STATES PATENTS

3,546,636	12/1970	DiPiazza	333/31 R
3,146,357	8/1964	Spallone	307/259
3,356,865	12/1967	Woster	333/31 R
3,453,564	7/1969	Russell	333/73 C

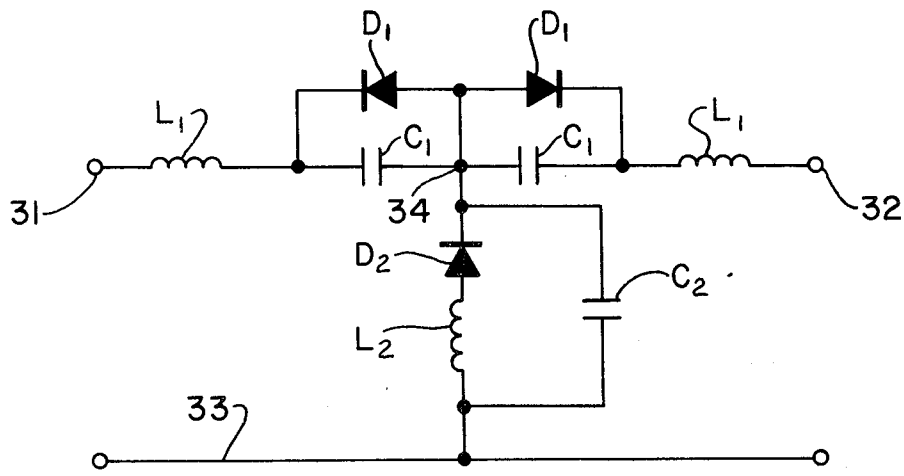
Primary Examiner—Paul L. Gensler

Attorney—Charles Hieken

[57] **ABSTRACT**

Three PIN diodes form a T junction. When the series diodes are forward biased, the shunt diode is reverse-biased to effectively form a low pass circuit. When the series diodes are reverse-biased, the shunt diodes are forward-biased to form effectively a high pass circuit. The cut off frequency of the low and high pass states are above and below, respectively, the operating band so that each T section selectively introduces a phase delay and advance in the low and high pass states, respectively.

1 Claim, 12 Drawing Figures



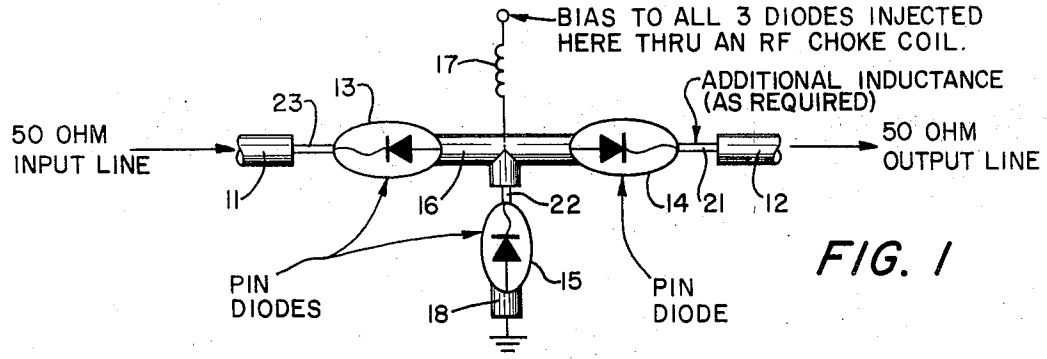


FIG. 1

STATE A
(SERIES DIODES—FORWARD BIASED
SHUNT DIODES—REVERSE BIASED)

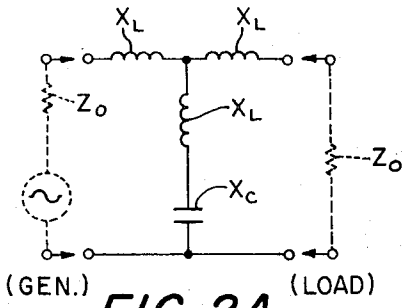


FIG. 2A

STATE B
(SERIES DIODES—REVERSE BIASED
SHUNT DIODES—FORWARD BIASED)

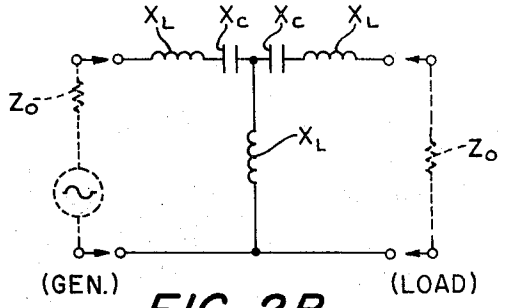


FIG. 2B

STATE A

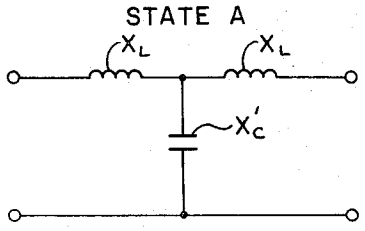


FIG. 3A

STATE B

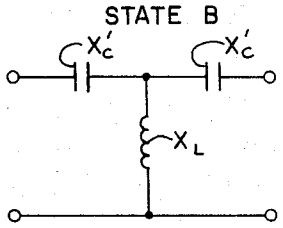


FIG. 3B

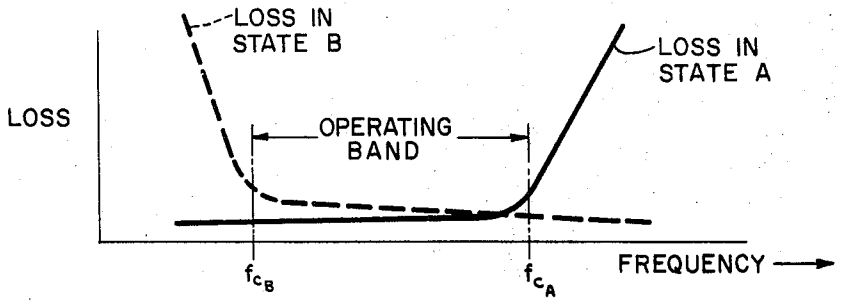


FIG. 4

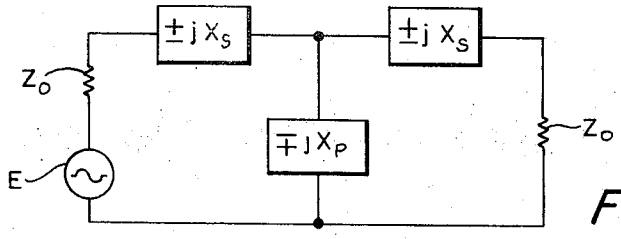


FIG. 5

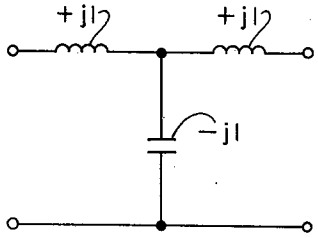


FIG. 6A

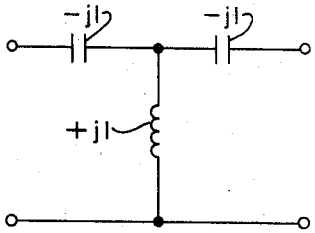


FIG. 6B

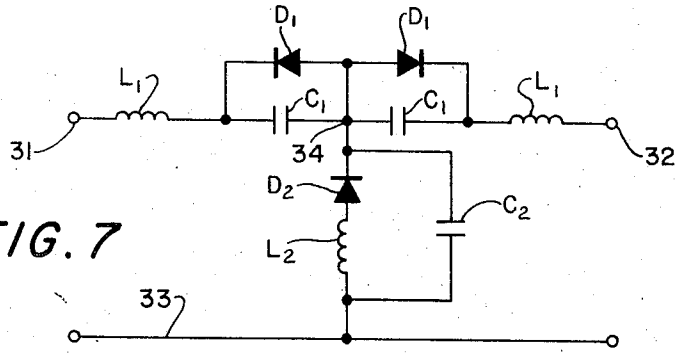


FIG. 7

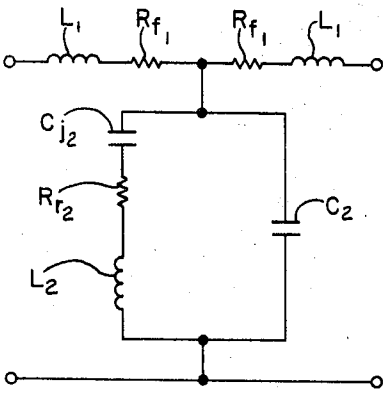


FIG. 8A

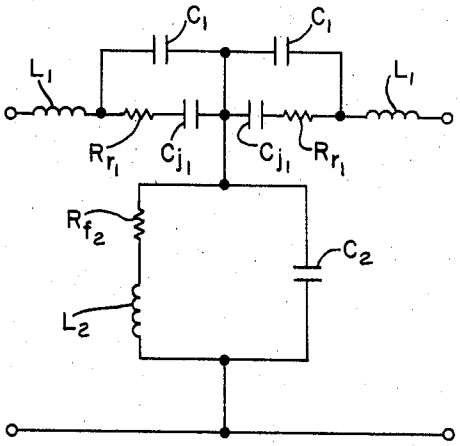


FIG. 8B

FILTER-TYPE DIGITAL DIODE PHASE SHIFTER

BACKGROUND OF THE INVENTION

The present invention relates in general to phase shifting and more particularly concerns a novel microwave phase shifter that advantageously employs PIN diodes to provide a reliable digital phase shifter with relatively compact inexpensive reliable apparatus. The invention realizes large phase changes at microwave frequencies in a very compact length.

It is an important object of the invention to provide an improved phase shifter.

It is another object of the invention to achieve the preceding object at microwave frequencies.

It is a further object of the invention to achieve one or more of the preceding objects while selectively effecting relatively large phase changes at microwave frequencies in a compact length.

It is still a further object of the invention to achieve one or more of the preceding objects with apparatus that is mechanically and electrically reliable and relatively easy and inexpensive to fabricate.

SUMMARY OF THE INVENTION

According to the invention, there is at least one filter section with means for selectively establishing low and high pass states with the cutoff frequencies in each state defining an overlapping hand of operation in both states to produce a phase difference in the overlapping band in the transmission characteristics of the two states. Preferably each section comprises microwave diodes which, when not conducting, may be characterized by an equivalent circuit having substantially an inductance in series with a capacitance to form a series resonant circuit resonant at a frequency above the overlapping or pass band of the system. Typically a section comprises PIN diodes, two of which comprise series arms and one of which comprises a shunt arm and means for biasing the series and shunt arms for conduction and nonconduction during mutually exclusive time intervals.

Numerous other features, objects, and advantages of the invention will become apparent from the following specification when read in connection with the accompanying drawing in which:

BRIEF DESCRIPTION OF THE DRAWING

FIG. **1** is a combined diagrammatic and schematic circuit diagram of a section according to the invention;

FIGS. **2A** and **2B** are schematic circuit diagrams of equivalent circuits of a section under states A and B, respectively, corresponding to low-pass and high-pass states, respectively;

FIGS. **3A** and **3B** are schematic circuit diagrams of the equivalent circuits of FIGS. **2A** and **2B**, respectively;

FIG. **4** is a graphical representation of insertion loss as a function of frequency to illustrate how the operating band is in the overlapping bands of low and high pass states;

FIG. **5** is a representation of the circuits of FIGS. **3A** and **3B** helpful in analysis for transmission phase shift;

FIGS. **6A** and **6B** are the circuits of FIGS. **3A** and **3B** with normalized values indicated for 180° phase shift;

FIG. **7** is a schematic circuit diagram of a section according to the invention offering certain practical advantages; and

FIGS. **8A** and **8B** are schematic circuit diagrams of the equivalent circuits of FIG. **7**.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

With reference now to the drawing, and more particularly FIG. **1** thereof, there is shown a combined pictorial schematic circuit representation of an embodiment of the invention. So as not to obscure the principles of the invention, details of the ground planes, terminals and the like are omitted, these aspects of the structure being apparent to those skilled in the art. A typical section may include an input line **11** and an output line **12** characterized by an impedance Z_o, typically 50 ohms. Three diodes, such as PIN diodes, **13, 14** and **15** are connected poled as shown to a junction section **16** which receives a biasing potential through r-f choke **17.** The anode of diode **15** is connected to ground through line section **18.** The cathodes of diodes **14, 15** and **16** may be connected in series with inductive sections **21, 22** and **23,** respectively, if additional series inductance is required for a specific operating frequency range.

When series diodes **14** and **13** are forward-biased, shunt diode **15** is reverse-biased. Conversely, when diode **15** is forward-biased, diodes **14** and **13** are reversed-biased.

The equivalent circuit of a diode, such as a PIN diode in a glass package, typically comprises at zero or reverse bias the series combination of lead inductance L, junction capacitance C_j and equivalent series resistance in the reverse-bias state R_r. At forward bias the lead inductance L is in series with an equivalent forward-bias sereis resistance R_f Neglecting losses, the equivalent circuit of a section in low-pass state A with the series diodes forward-biased and the shunt diode reverse-biased is shown in FIG. **2A** and in high-pass state B with the series diodes reverse-biased and the shunt diode forward-biased is shown in FIG. **2B.** X_L is the inductive reactance of the diode lead inductance in series with an inductive section. The impedance X_c is the capacitive reactance of a reverse-biased junction. If the circuit is operated below the series resonance of an arm, X_L is less than X_c and the circuits of FIGS. **2A** and **2B** may be represented by the circuits of FIGS. **3A** and **3B**, respectively. $X_c' = |X_L - X_c|$. As the bias state of the diodes are switched, the circuit changes from a low pass filter to a high pass filter. By establishing the parameter values so that the cutoff frequency of the low pass state is above the operating band and that of the high pass state is below the operating band, the phase shifter will exhibit low insertion loss in both states in the operating band as indicated in FIG. **4.** However, the low pass filter in state A imparts a phase delay while the high pass filter in state B imparts a phase advance. The result is a low-loss transmission section in the operating band having means for selectively shifting between phase delay and phase advance.

Referring to FIG. **5,** there is shown a representation of the arms in the circuit sections of FIGS. **2A** and **2B** helpful in analyzing the phase delay per section.

$$\Delta\Phi = \Phi_A - \Phi_B = 2\tan^{-1}[1 - (x_p - x_s)^2 + x_p 2]/2 \quad (x_p - x_s)$$

As an example, if $Z_o = 50 = X_L = X_c' = 50$ ohms ($X_c = 100$ ohms), the circuit may be represented on a normalized basis as having a vector impedance $+j$ in the series arms and $-j$ in the shunt arm in state A as shown

in FIG. 6A. In state B the series arm impedances are each $-j$ and the shunt arm impedance is $+j$ as shown in FIG. 6B. By inspection in this special case it can be seen that the phase delay in state A is $+90°$ and $-90°$ in state B to produce a change of 180° between states A and B with one section. The physical realization in strip line is a unit less than an inch long at microwave frequencies while in microstrip the length would be less than one-half inch. Low values of phase shift may be obtained by changing the values of L and C so that x_s is less than unity and x_p is greater than unity in the equation for phase delay above.

In an actual embodiment of the invention at a frequency of 2.0 GHz, the loss in state A was only 1.60db and that in state B 3.8 db while providing a phase shift difference of 174° between the two states. That embodiment included 0.6 picofarad glass PIN diodes in the series arms and a 0.4 picofarad PIN diode in the shunt arm.

Referring to FIG. 7, there is shown a schematic circuit diagram of a preferred embodiment of the invention for even further reducing insertion loss. This embodiment includes input and output terminals **31** and **32** and a common or grounded line **33.** Each series branch comprises a diode D1 shunted by a capacitor of value C1 in series with an effective inductance of value L1 between a respective one of input and output terminals **32** and junction **34** to which a biasing potential is applied. The shunt network comprises a diode D2 in series with an inductance L2 between junction **34** and grounded line **33,** the latter series combination being shunted by a capacitance of value C2. Diodes D1 and D2 are extremely low capacitance diodes having a capacitance typically 0.05 to 0.15 picofarads and function essentially only as switches. Capacitors C1 and C2 are preferably high Q chip capacitors. The shunt arm comprises a parallel LC resonant circuit and is advantageous because it leads to more practical element values. Principles of operation are essentially those described above in connection with the circuit in FIG. **2.**

In low pass state A, diodes D1 are effectively short circuits while diode D2 is an open circuit. In high pass state B diode D2 is essentially a short circuit while diodes D1 are open circuits. Specific values of L1 and C1, L2 and C2 are chosen so that the circuit then approximates a high pass T filter. With this circuit up to 180° of phase change can be obtained with less than one db loss.

Referring to FIGS. 8A and 8B, there are shown equivalent circuits of the circuit of FIG. 7 in the A and B states respectively. In the A and B states the series diodes are forward-biased and reverse-biased, respectively, and the shunt diode is reverse-biased and forward-biased, respectively. For determining phase shift, it is convenient to assume that the resistances are negligible and may be neglected. Then the transmission phase shift in the two biased states is given by the following expression.

$$\Phi = \tan^{-1} \frac{b(Z_0^2 + 2x/b - x^2)}{2Z_0(1 - xb)}$$

where $x = \omega L_1$ and $b \approx \omega\ (C_2 + C_{j2}) \approx \omega\ C_2$ for the A state;

$x \approx \omega L_1 - 1/\omega C_1$, and

$b = \omega C_2 - 1/\omega L_2$ for the B state for the bias states described in FIG. 8B. It is assumed that the junction capacitance of the diodes is so small that $1/\omega C_{j2} >> \omega L_2$; $C_{j2} << C_2$; and $C_{j1} << C_1$.

In other words:

$$\Phi A = \tan^{-1} \left\{ \frac{B_A + 2X_A - X_A^2 B_A}{2(1 - X_A B_A)} \right\}$$

where $X_A \equiv | \omega L_1/Z_o |$ and $B_A \equiv | \omega C_2/Y_o |$ in the A state. In the B state it is assumed that $\omega L_1 < 1/\omega C_1$ and $\omega C_2 < 1/\omega L_2$, then x and b are negative so that the transmission phase shift

$$\Phi_B = \tan^{-1} \left\{ -\frac{B_B + 2X_B - X_B^2}{2(1 - X_B B_B)} \right\}$$

where $X_B = \frac{(\omega L_1 - 1/\omega C_1)}{Z_0}$ and $B_B = \frac{(\omega C_2 - 1/\omega L_2)}{Y_0}$.

If $X_A = X_B = B_A = B_B = 1$ at midband, then the circuits of FIGS. 8A and 8B correspond to the circuits of FIGS. 6A and 6B described above.

It is convenient to define impedance levels in the A and B states as:

$K_A = \sqrt{(2L_1/C_2)}$ and $K_B = \sqrt{(L_{e_2}/2C_{e_1})}$ respectively, and cutoff frequencies

$f_A = (1/2\pi)\sqrt{(2/L_1C_2)}$ and $f_B = (1/2\pi)\sqrt{(1/2L_{e_2}C_{e_1})}$ where for frequencies which satisfy $\omega^2 < (1/L_1C_1)$ and $\omega^2 < (1/L_2C_2)$, $L_{e_2} = L_2/(1 - \omega^2 L_2 C_2)$ and $C_{e_1} = C_1/(1 - \omega^2 L_1 C_1)$. Using these definitions $X_B = (1/\omega C_{e_1} Z_0)$ and $B_B = (Z_0/\omega L_{e_2})$.

In order to have a reasonably well-matched structure, K_A and K_B should be close to Z_o. Choosing $K_A = \sqrt{2Z_o}$ and $K_B = (Z_0/\sqrt{2})$, $Z_0 = \sqrt{(L_1/C_2)} = \sqrt{L_{e_2}/C_{e_1}}$, or $(L_1/C_2) = (L_{e_2}/C_{e_1}) = Z_0^2$. This results in $X_A = B_A$ and $X_B = B_B$. Similarly, a reasonable compromise for setting the low and high pass cutoff is $(f_A/f_o) = (f_o/f_B)$ where f_o = center frequency of the operating band. This results in

$$f_o = 1/2\pi\sqrt{L_1C_{e_1}} = 1/2\pi\sqrt{L_{e_2}C_2}.$$

Hence, $f_A/f_o = \sqrt{2L_{e_2}/L_{e_1}}$ and $f_B/f_o = \sqrt{L_1/2L_{e_2}}$. Manipulation of the above expressions for f_o leads to

$$L_2 = 1/(2\ \omega_o{}^2 C_2) \text{ and } C_1 = 1/(2\ \omega_o{}^2 L_1).$$

Given Z_o, f_o and the required $\Delta\Phi$ at midband, the following steps may be followed to determine parameter values. 1. Find the midband value of X_A (which is $\omega w_o L_1/Z_o$) for the required value of $\Delta\Phi$ from the following expression.

$$X_A\ [(3 - X_A^2)/(1 - X_A^2)] = 2 \tan \Delta\Phi/2.$$

The values of X_A for common values of $\Delta\Phi$ are given in the following table. (Note that to a first approximation $2 \tan \Delta\Phi/2 = 3X_A$.)

Φ	0	11¼°	22½°	45°	90°	180°
$\omega L_1/Z_o$	0	0.07	0.14	0.26	0.53	1

2. Determine C_2 from the equation.

$$C_2 = L_1/Z_o^2$$

3. Determine L_2 and C_1 from the equations.

$$L_2 = 1/2\omega_o{}^2 C_2 \text{ and } C_1 = 1/2\omega_o{}^2 L_1.$$

It can be shown that values of $\Delta\Phi$ within 10 percent of a predetermined nominal value may be achieved over a 20 to 30 percent frequency range. However, greater uniformity of phase shift may be achieved within a frequency range not exactly centered about

the nominal center frequency f_o. It may be advantageous to plot $\Phi A - \Phi B$ as a function of frequency experimentally or through computer simulation techniques in connection with selecting an optimum frequency range for a predetermined phase shift.

It can be shown that good VSWR in both the A and B states can be obtained over a relatively wide bandwidth for a phase difference up to 90°. For a phase difference of 180°, the VSWR is good over a bandwidth of 10 to 15 percent of center frequency.

It can also be shown that the insertion loss is roughly constant over a 20 percent bandwidth and less than a decibel for a 90° phase shift, and even smaller for lesser phase shifts.

It can also be shown that a unit operating at C band can readily handle 10 watts of incident r-f power. For $Z_o = 50$ ohms and 200 volt PIN diodes, the maximum allowable r-f power before appreciable nonlinearity occurs is about 800 watts peak. For 400 volt diodes, the allowable peak power is roughly 3 kilowatts.

The invention is thus capable of wide band low-loss performance in an exceptionally compact structure especially suitable for microstrip fabrication.

There has been described a novel digital phase shifter characterized by relatively low insertion loss, relatively large available phase shift in an exceptionally compact physical structure while operating reliably and being relatively inexpensive to fabricate. It is evident that those skilled in the art may now make numerous modifications and uses of and departures from the specific embodiments described herein without departing from the inventive concepts. Consequently, the invention is to be construed as embracing each and every novel feature and novel combination of features present in or possessed by the apparatus and techniques herein disclosed and limited solely by the spirit and scope of the appended claims.

What is claimed is:

1. Microwave phase shifting apparatus comprising,

means defining an input and output,

means including inductive and capacitive elements intercoupling said input and output,

means including nonlinear elements for selectively shifting the network formed by said elements between a low pass state and a high pass state,

the parameter values of said elements coacting to establish the cutoff frequency in said high pass state below the cutoff frequency in said low pass state to define therebetween an operating band in which the phase shift imparted between said input and said output is different in said low pass state than in said high pass state,

said nonlinear elements being unilaterally conducting devices and said means for selectively shifting comprising means for selectively rendering said unilaterally conducting devices conducting and nonconducting,

there being first and second ones of said unilaterally conducting devices in series arms between said input and said output and a third of said unilaterally conducting devices connected between the junction of said first and second devices and a common line,

and means for establishing said first state by rendering said first and second devices conductive and said third device nonconductive and for establishing said second state by rendering said first and second devices nonconductive and said third device conductive,

said third device being in series with an inductive element and the latter series combination being shunted by a capacative element to form a shunt parallel resonant circuit,

each of said first and second devices shunting a respective capacitive element and in series with a respective inductive element.

* * * * *