Small–size delay line based on a periodically loaded waveguide

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***Abstract* — A delay line design is proposed which is based on a ceramic-strip loaded, slotted rectangular waveguide. The design combines very small size with moderate bandwidth (5% ... 10%) and low insertion loss (< 0.50 dB/ns at 2 GHz). The delay line employs a periodic structure of coupled resonators and is rather insensitive to manufacturing tolerances.**

I. INTRODUCTION

Delay lines are important elements in linearized power amplifiers in modern communication systems [1]. Typical requirements include delays of 10...20ns, low power, medium insertion loss, medium bandwidth (5% ... 10%), etc.

Coaxial lines of appropriate length have been used frequently in the past. Advantageous are their simplicity, linearity, and the low loss (depends on diameter). However, they are bulky and generally incompatible with automated assembly processes.

Miniaturized ceramic bandpass filters and lumped component filters are going to replace coaxial delay lines at low frequencies (say, below 3 GHz), showing comparable loss, acceptable transmission flatness and smaller size. A general drawback of bandpass filter delay lines (having e.g. Tchebyschef or Bessel characteristics) is the need for tight tolerances and/or tuning. The number of filter sections (resonators) grows with delay, bandwidth, and flatness [2]. For example, a 7 resonator filter with an additional delay correction circuit produces flat 18ns delay over only 3% bandwidth [3].

On the other hand, low–pass ladder networks (for instance, corrugated waveguides or other slow-wave structures) avoid the tolerance-critical resonators and couplings of multiresonator bandpass filters. They are, however, bulkier than the bandpass filters because they need much more reactive elements in order to achieve a specific group delay [2].

The use of high permittivity dielectrics may significantly reduce the volume of the device. However, if metallized parts are involved, conduction currents may become the source of excessive loss. Therefore, planar circuits on high permittivity substrates should avoid high impedance lines and other patterns with high current density.

In the following, a bandpass ladder network delay line design is described which combines several important properties. First, as a periodic network (ladder network) the structure avoids strong couplings and is therefore quite insensitive to tolerances. Second, this new delay line is geometrically very small due to the use of high permittivity dielectric. In order to maintain low insertion loss, parts of high current density has been avoided as much as possible. Third, the structure is expected be easy to manufacture since the ceramic need not to be machined. In fact, only plating, etching, and soldering of the ceramic are necessary.

II. DELAY LINE DESIGN

A transmission line can be regarded as a cascade connection of series inductances and shunt capacitances (Fig. 1).

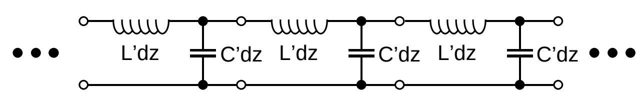

Fig. 1: *Section of a transmission line*

The inductances store mainly magnetic field energy and the capacitors store the electric field energy. If a wave travels down the line, the energy is converted from being magnetic to electric and *vice versa*. The larger the amount of energy stored per unit length, the lower the wave velocity

$$v = \frac{1}{\sqrt{L'C'}} = \frac{1}{\sqrt{m_0 e_0 e_{eff}}}$$

The wave can be slowed down by enlarging *L'* and/or *C'* either continuously along the line or periodically. For example, a continuous increase of *C'* is achieved by using a high permittivity substrate for a microstrip line. Or, the periodic loading of a corrugated waveguide enlarges both *L'* and *C'* and slows down the wave.

A bandpass filter as shown in Fig. 2 is known to give a larger delay in the passband than the lowpass network shown in Fig. 1 does. For a bandpass filter, however, group delay and/or transmission loss may show significant ripples [2]. The proposed delay line is based on coupled resonators and can be mapped onto the bandpass ladder network of Fig. 2.

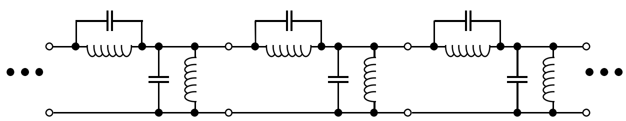

Fig. 2: *Schematic of a delay transmission line*

A drawing of the proposed delay line (2½ periods) is shown in Fig. 3. A flat ceramic slab points in the direction of wave propagation. This slab is periodically surrounded by metal, thus forming sections of dielectric slab loaded rectangular waveguides (section *A* in Fig. 3), separated by unmetallized open dielectric sections (section *B* in Fig. 3). All sections must be much shorter than the guided wavelength of the supported mode.

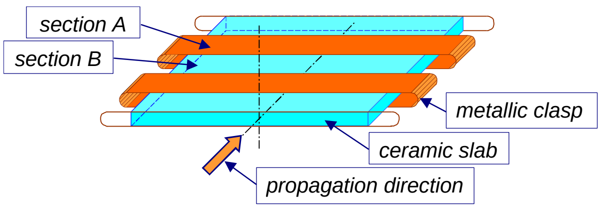

Fig. 3: *Schematic view of the proposed delay line.*

Most of the losses of the delay line structure are conductor losses and occur in sections *A*. Therefore, low surface roughness and large metallic conductivity are important. For this reason, the sides of the ceramic strip are not metallized directly, and rounded clasps are used resulting in lower loss. Practically, the top-to-bottom connection of the metallic clasp can be made highly conductive by using via holes of printed circuit board technology (the permittivity and the potential dielectric loss of these dielectrics does not affect the performance).

The delay line structure evolved from a dielectric slab filled rectangular waveguide. Section *A* may support a TE_{10}–like mode of very low impedance and quite large propagation constant. This section is, however, electrically very short in propagation direction ($\beta\Delta z \approx 4°$ ... 8°). Due to the metallic pattern, currents are forced to flow in transverse direction. Therefore, there is almost no magnetic field component in the transverse plane.

Section *B* could support a mode similar to the TM_1 slab mode (this mode has zero cutoff and the required magnetic wall symmetry). Because the slab is thin, this mode is only weakly guided and has a propagation constant almost equal to that of propagation in air. Since the section length is so small ($\beta\Delta z$ <≈ 1°)., and the excitation with a low-impedance TE_{10} mode is rather weak, the slab mode is not excited and section *B* acts as a coupling region with decaying fields.

Details become clear from a look at the transition between sections *A* and *B*. Note the huge dielectric contrast between the slab region and the air region. The electric field remains almost completely concentrated in section *A*. Some fringing E-field enters section *B* creating a weak longitudinal field. Due to the normal continuity of the electric displacement, there is almost no transverse E-field inside the dielectric of section *B*. Fig. 4 shows this effect known from electrostatics.

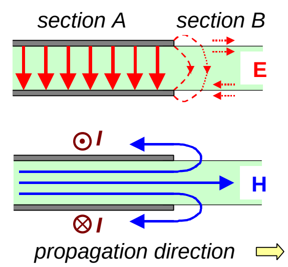

Fig. 4: *Transition between sections* A *and* B *(sideview) showing fringing E-field (top) and H–field (bottom).*

Thus, sections *A* are in fact open-ended at both sides. That is, magnetic field lines point in propagation direction at the sides of the slab, while the electric field is concentrated in the center of the slab. The current flows around the clasp (see Fig. 5). Thus, each metallic clasp forms a resonator.

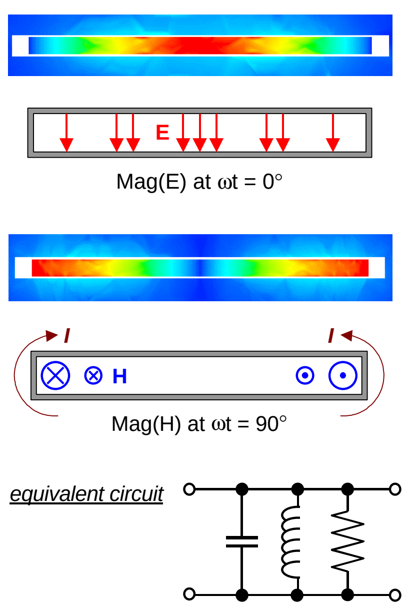

Fig. 5: *Fields and currents in the cross section of the dielectric loaded rectangular waveguide (center of section* A*).*

Section *B* separates neighboring clasps by forcing the E-field out of the slab. The E-field intensity in section *B* is much smaller than in section *A*. Neighboring clasps will couple mostly through the magnetic fields, which are not affected by the dielectric-air interface of section *B*. Fig. 6 shows the fields in the cross section of section *B*.

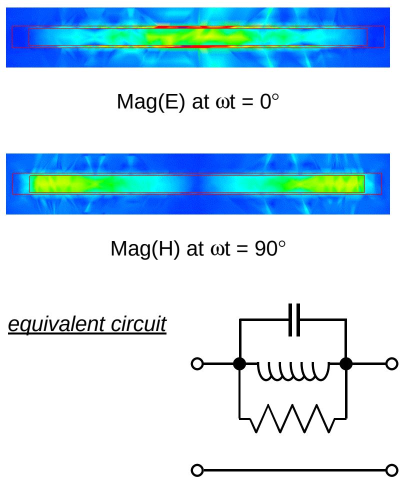

Fig. 6: *Fields in the cross section of the open part (center of section* B*). The respective magnitudes of the electric and magnetic fields are much smaller than in section A. They are scaled to the same values as in Fig. 5.*

The delay line structure shows some similarity to a chain of edge coupled, halfwave microstrip line resonators, each of them being shorted at both ends. The structure is different in that bot metallic plates (top and bottom) are patterned identically, which results in weaker fringing fields (thus better separation of the resonators and smaller overall size) and lower overall conductive loss if compared to a similar microstrip structure.

All sections of the delay line structure together form a ladder network as shown in Fig. 2 with all shunt resonator elements being geometrically quite small. Although the line is unshielded and discontinuous, there is almost no radiation, because the structure is small compared to the free–space wavelength and only low–intensity fields leak out into free–space. In the example of a 20ns delay line discussed below, the simulated radiation loss was only about 2%.

Extensive simulations have been performed in order to optimize delay per length and to minimize losses. The final geometrical parameters of the delay line are given in table I.

Circuit parameters were extracted from field simulations of single sections and pairs of sections. To do so, scattering parameters of both field and circuit simulations have been forced to match over 10% bandwidth. The equivalent ladder network parameters found are given in Fig. 7. Although the physical structure can well be subdivided in resonators (sections *A*) and couplings (sections *B*), the actual values of the reactance elements are somewhat arbitrary. They can, however, considered reasonable in terms of resonance frequency and because resonator coupling is mainly inductive and the losses are concentrated in the clasp resonator.

dielectric slab	width 8.0mm, height 0.508mm, ε_{rel} = 80, tan δ = 0.0035
metallization	thickness 50µm, $\sigma = 45 \times 10^6$ S/m
guide section "A"	length 0.4mm, width 10.0mm + half circles
slab section "B"	length 0.5mm

Table I.: *Geometrical and electrical parameters of the simulated delay line structure.*

Cascading 28.5 periods of the delay structure (geometrical length 25.6mm), a delay of approx. 20ns is found. This corresponds to a group velocity of about c_0 / v_{gr} » 230. Fig. 8 shows field magnitudes in the symmetry plane perpendicular to the magnetic wall at 2 GHz. The large phase difference from one clasp to the next is clearly shown. Fig. 9 shows the results from the circuit simulation (network shown in Fig. 7) as well as those from 3D field simulation (HFSS). The insertion loss is found between 0.35dB/ns and 0.45dB/ns over a 200MHz (10%) bandwidth.

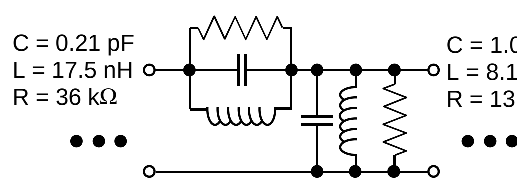

Fig. 7: *Extracted circuit parameters for the delay line.*

A simple possibility to feed the delay line structure with a 50Ω microstrip line on ε_{rel} = 10.2 substrate is shown in Fig. 10. The influence of the microstrip feed on input match and insertion loss of the overall structure can be neglected over the 10% bandwidth.

According to our simulation results the proposed delay line is competitive in terms of insertion loss compared to either ceramic filters, lumped element filters, or small-sized coaxial cables. The delay flatness needs either some design improvements or a correction circuit. The delay ripple is an inherent drawback of the simple periodic ladder network design. However, the geometrical size of the proposed delay line is exceptionally small.

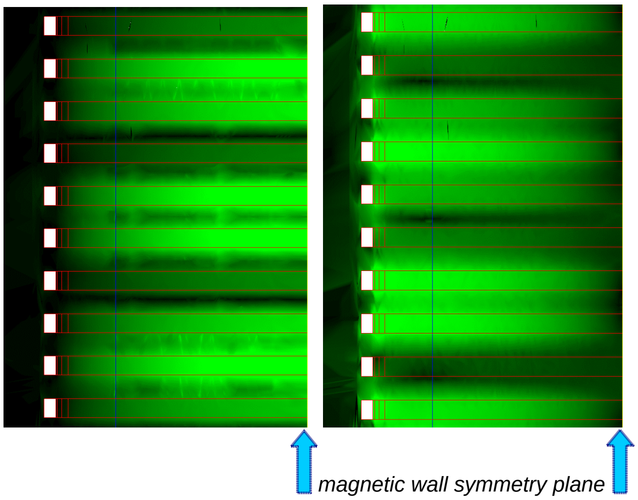

Fig. 8: *Electric (left) and magnetic (right) field magnitudes in the symmetry plane perpendicular to the magnetic wall (top view, wave propagation upwards) at 2 GHz.*

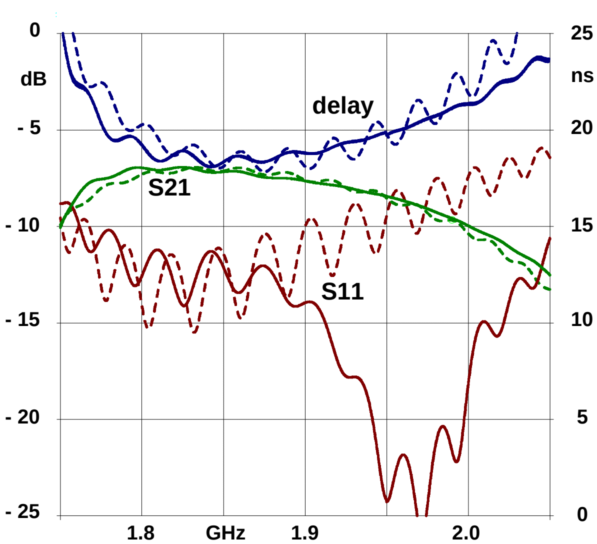

Fig. 9: *Insertion loss, input match, and group delay as obtained from 3D field simulations (solid lines) and circuit simulation of the ladder network (dashed lines).*

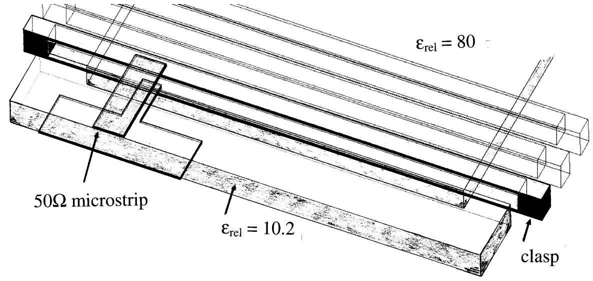

Fig. 10: *Microstrip feed for the delay line structure. Substrate e_{rel} = 10.2 / thickness 0.635mm. Tuning is possible by varying the feed position on the clasp.*

III. CONCLUSION

A new concept of an ultra small delay line based on a periodic arrangement of small resonators has been introduced. Short sections of a dielectric loaded waveguide resonating in transverse mode are coupled through unshielded dielectric slab sections.

The structure can be considered as a circuit of side–coupled half–wave parallel line resonators. These resonators are, however, almost entirely inductively coupled.

A cascade of coupled resonators was simulated with a 3D field simulator and equivalent circuit parameters were extracted. Assuming realistic metallic (Au) and dielectric losses, a delay of 19ns over 25mm geometrical length, an insertion loss of < 0.50dB/ns, and a bandwidth of 10% around 1900 MHz were obtained.

The insertion loss of the structure can be minimized by reducing conductor losses. This can be accomplished by using highly conductive metal in the high–current parts, and/or by increasing the height of the dielectric slab, and/or by using longer (in propagation direction) metallic clasps. These measures will increase the complexity and/or the volume of the structure.

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