Resistive power divider for magneto-inductive waveguides

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Addressing the need for passive magneto-inductive components, a lumped-element symmetric power divider has been designed and realised for a magneto-inductive cable with the resonant frequency of 95 MHz and the passband between 73 and 174 MHz. In agreement with the theory, the measured coupling loss is 6 dB for most of the passband independent of the input port. Having proved useful for magneto-inductive waveguides, the approach can be employed for the design of further passive components.

Introduction: Open LC-resonators can couple to each other by magnetic induction. Waveguides based on this principle, known as magneto-inductive (MI) waveguides [1], have applications for signal detection and amplification in magnetic resonance imaging [1], signal processing [2], data transmission [3], and underground sensor networks [4]. A recent waveguide design in the form of a thin-film cable [5] provides improved transmission characteristics (low propagation loss, wide passband, and impedance matching) and eliminates non-nearest neighbour coupling.

Further progress requires passive components for MI waveguides: couplers, dividers, filters etc. A number of such devices based on magnetic coupling between LC-resonators was studied theoretically (see e.g. [6]). An alternative approach is to rely on lumped elements. It is often pursued in microwave design [7], but for MI components the challenge is to achieve broadband performance; while the characteristic impedance of standard microwave waveguides is real and constant, that of MI waveguides is complex and frequency dependent. This Letter presents a design and a realisation of a broadband lumped-element divider for MI waveguides.

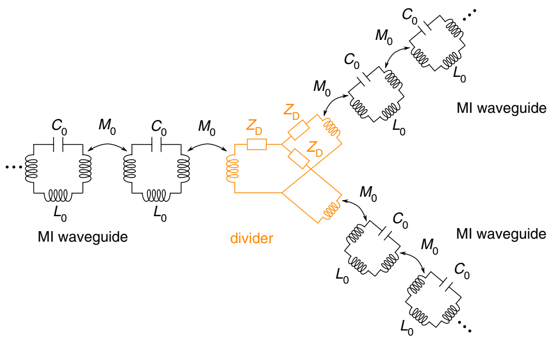

Fig. 1 *Three-port symmetric power divider connected to MI waveguides*

Divider design: Fig. 1 shows a schematic presentation of the three-port divider together with sections of MI waveguides. The symmetric divider contains three equal unknown impedances, Z_{D}, the value of which can be found by the following method [6]. A wave incident on the divider in one of the ports will be partially reflected from the same port and partially transmitted through the other two ports. Then, denoting the incident port as 1, and the transmitting ports as 2 and 3, one can write for the currents in the waveguides $I_{1,n} = I\exp(-\mathrm{j}nka) + R\exp(\mathrm{j}nka)$ and $I_{2,n} = I_{3,n} = T\exp(-\mathrm{j}nka)$. Here, I, R, and T are the amplitudes of the incident, reflected, and transmitted waves, respectively, and n is the element number. The phase change per element, ka, is given by the dispersion relation $1 - \omega_0^2/\omega^2 + \kappa\cos(\mathrm{ka}) = 0$ [1], where ω is the angular frequency, $\omega_0 = 1/\sqrt{(L_0C_0)}$ is the angular resonant frequency, and $\kappa = 2M_0/L_0$ is the coupling coefficient, see Fig. 1. Writing Kirchhoff's equations for the currents in the divider and setting the reflection coefficient, R, to zero, one finds the value of Z_{D} as

$$Z_{\mathrm{D}} = \frac{Z_0 + Z_{\mathrm{c}}*}{3}$$

where $Z_0 = \mathrm{j}\omega L_0 + 1/(\mathrm{j}\omega C_0)$ is the impedance of an element and $Z_{\mathrm{c}} = \mathrm{j}\omega M_0\exp(-\mathrm{j}ka)$ is the characteristic impedance of the MI waveguide. The asterisk denotes complex conjugation. A simple but accurate approximation is to present Z_{c}^* as $Z_{\mathrm{c}}^* = \mathrm{j}\omega L_0/2 + 1/(2\mathrm{j}\omega C_0) + R$, where $R = \omega_0 M_0$ is the mid-band impedance [8]. Then, one gets for the divider impedance

$$Z_{\mathrm{D}} = j\omega\frac{L_0}{2} + \frac{1}{2j\omega C_0} + \frac{R}{3}$$

Fig. 2 shows the equivalent circuit of the corresponding divider.

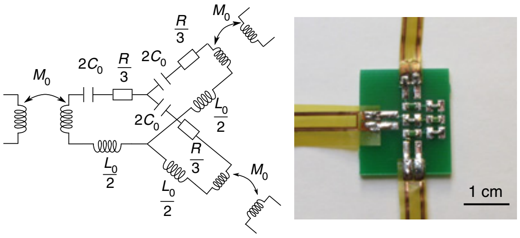

Fig. 2 *The divider: equivalent circuit and photograph*

Divider realisation: Dividers were fabricated for a thin-film MI cable made by double-sided patterning of copper-clad Kapton [5]. In this cable design, the elements combine loop inductors, positioned on both sides of the cable, with integrated parallel-plate capacitors. The resonant frequency of the elements was 95 MHz; the coupling coefficient between the nearest neighbours was 0.7, for which the calculated pass band was between 73 and 174 MHz. The cable would, therefore, be suitable for operation at frequencies used in magnetic resonance imaging (127.6 MHz for ^{1}H MRI at the magnetic field of 3T). At the resonant frequency, the cable had the characteristic impedance of 50 Ω and the loss per element of about 0.25 dB.

When cut, the cable is terminated by inductors with the value $L_0/2$. To construct the divider, capacitors (22 pF) and resistors (16.7 Ω) were arranged on a standard FR-4 printed circuit board according to the circuit of Fig. 2 (also showing a photograph of the divider). Three MI cables, one containing 17 (port 1) and the other two seven elements (ports 2 and 3), were connected directly to the boards. The other ends of the cables were terminated by resonant coupling transducers [8]. Electrical characteristics were measured by connecting two of the cables to a network analyser (Agilent E5061A) and terminating the third by a 50 Ω resistor.

Independent of the input port, the divider equally split the power in the other two ports. Fig. 3 shows the measured and calculated values of $|S_{21}|$ and $|S_{31}|$. The frequency characteristics are the same for port 2 and port 3. The maximum values of $|S_{21}|$ and $|S_{31}|$ are -12 dB at the resonant frequency. This value is a sum of the propagation loss (0.25 dB/element × (17 + 7) = 6 dB) and 6 dB coupling loss of the symmetric divider. The transmission characteristics are flat between 77 and 139 MHz, about 60% of the passband. The measured values agree well with the theoretical calculations. Similar results were obtained using ports 2 and 3 as input.

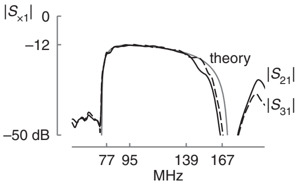

Fig. 3 *Measured and calculated frequency characteristics for $|S_{21}|$ and $|S_{31}|$ confirm equal power division*

Conclusion: The lumped element divider provides equal power division independent of the input port for most of the passband, flat transmission characteristics for 60% of it, and it is simple to fabricate. This fruitful approach can be used for the design of other MI components.

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One or more of the Figures in this Letter are available in colour online.

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