Experimental knitted, textile frequency selective surfaces

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A new approach to the manufacture of conducting textiles for operation at microwave frequencies is reported. The technique investigated utilises a commercial flat-bed knitting process which is configured to use conducting yarns to produce large area, patterned, conducting textiles in an efficient manner which is amenable to mass production. The computerised flat-bed knitting system is used to manufacture example frequency selective surfaces (FSSs) using silver coated nylon yarn combined with a polyester base yarn. Reflectivity measurements are presented to confirm the basic operation of both a lowpass and a highpass knitted, textile FSS.

Introduction: Traditionally, electromagnetic components are often manufactured using sheet metal or printed circuit board techniques. However, over the past decade new materials and manufacturing techniques have been developed that permit the creation of electromagnetic structures, such as antennas and transmission-lines, using conducting textiles [1, 2].

Electromagnetic structures based on conducting textiles have certain advantages over equivalent structures constructed from conventional materials. Textile structures offer advantages such as light weight, flexibility, softness, and high-strength-to-weight ratios. A unique advantage of electromagnetic structures based on textiles is that they can be integrated into clothing to provide functions such as on-body and off-body communications. Functional conducting textiles may also be integrated into composite structures where they provide a light weight and flexible alternative to conventional structures based on circuit-board technology. Advanced textile manufacturing techniques, such as computerised flat-bed knitting, can also be used to create a variety of three dimentional (3D) and conformal structures to prescribed geometries [3].

Much of the previously published work on conducting textiles at RF frequencies considers structures constructed from combinations of traditional (non-conducting textiles) with commercially available conducting textiles such as Zelt to form hybrid structures [4]. The disadvantage of this approach, particularly when applied to complex structures such as frequency selective surfaces (FSSs), is that the conducting textile needs to be 'cut-to-shape' and then attached to the non-conducting textile substrate using adhesive or some other means. This is obviously a time-consuming process that is not amenable to mass manufacturing and alternatives are sought. One alternative technique that has been investigated is the use of computerised embroidery in which a conducting yarn is used to embroider conducting features, such as a patch antenna, onto a non-conducting textile base, or substrate, layer [5]. Although computerised embroidery is a step forward with regard to efficient manufacturing, it is still a relatively slow process and the conducting surfaces created often suffer from poor continuous conductivity.

In this Letter we investigate the use of another textile manufacturing process – knitting – to fabricate conducting textile structures. Knitting is a very old and traditional process that has been revolutionised over the past few decades to allow the efficient, commercial manufacture of a wide variety of textile products using advanced, large-scale, flat-bed knitting machines under computer control and driven by advanced CAD software interfaces [6]. The computerised flat-bed knitting process can easily be used for the manufacture of large-area textile structures with repeated patterns and is therefore ideally suited to the manufacture of periodic structures such as FSSs and meta-material surfaces. FSSs typically consist of a grid of periodically arranged conducting patches on a dielectric substrate. At microwave frequencies, FSSs can act as transmission or reflection filter elements and can be configured for lowpass, highpass, bandpass or bandstop operation. Applications of FSSs include dichroic sub-reflectors for multi-band reflector antennas, radomes, electromagnetic shielding, and as components in radar absorbers and electromagnetic bangap (EBG) structures.

In this Letter, and for the first time, we report experimental results obtained from two experimental knitted FSS structures designed to exhibit capacitive (lowpass) and inductive (highpass) responses.

Knitting process: Knitted structures consist of stitches (loops) which are arranged in courses (rows) and wales (columns) and bound to the stitches in adjacent rows. Stitch is the primary yarn binding element of a knitted structure, which is created when three yarn loops are interconnected together resulting in four yarn contact regions [7]. The contact mechanics at the contact areas are very complex and their behaviour is not yet fully understood. If an incompressible and inextensible yarn (idealised yarn) is used then each contact region can be represented by a contact point. However, for all standard yarns the yarn cross-over regions of a stitch can be represented as a line contact at the relaxed state shifting into an area contact as the knitted structure undergoes mechanical loading. Therefore the yarn cross-over regions of a stitch can be considered as a short circuiting point for modelling the electrical equivalent circuit of an electrically conductive knitted structure, i.e. each yarn cross-over region of a stitch will act as a node in a resistive mesh. The problem of equivalent surface impedance is much more complicated at microwave frequencies where inductive and capacitive impedance must be considered. The complexity of the RF analysis problem is also compounded as mutual coupling between individual conducting yarns must also be considered.

For the above reasons, this Letter does not attempt to provide comparative simulation results and instead we validate our work by showing that the measured characteristics of typical FSS designs based on inductive (grid structures) and capacitive (conducting patch) structures show the expected generic responses.

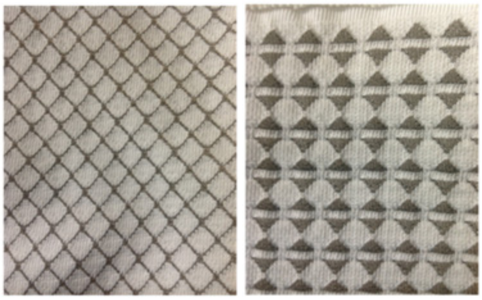

Fig. 1 *Example sections of two knitted, conducting textile FSSs*

a Conducting grid
b Conducting patch
White area knitted from polyester yarn; dark regions knitted from conducting yarn

Experimental knitted FSS: The knitting process, described above, was used to manufacture two FSS structures, samples of which are shown in Fig. 1. The first (Fig. 1*a*) is a typical inductive FFS and consists of a square conducing grid of side length equal to approximately 8mm. The second structure, shown in Fig. 1*b* consists of a periodic array of double triangular patch elements. Both FSS structures were knitted using a Shima Seiki SWG091N (gauge 15) computerised flat-bed knitting machine. The non-conducting base yarn was polyester and the conducting yarn ($\simeq 4\Omega cm^{-1}$) was formed by embedding silver nano particles on the surface of a 235 Denier 34 filament Polyamide 6.6 yarn [8]. The sample sizes of both the inductive and the capacitive FSS was approximately 300 by 300mm

Measurements: The knitted textile FSSs are inherently flexible structures, but to characterise them they were arranged and measured as flat planar surfaces. To facilitate the measurements the textile FSS was placed over a 30 by 30cm square, low-loss, polystyrene slab (3 cm deep) and gently stretched in both linear dimensions to equalise any distortion and to produce a flat surface with a symmetrical surface pattern. The normal incidence, free-space reflectivity (S11) characteristics of the textile FSS were measured in a fully calibrated NRL arch using an automated measurement system employing an Agilent 8510B vector network analyser. The reference, calibration standard was a flat aluminium plate of equivalent size (30 by 30cm). The measurements were performed in a dedicated anechoic chamber and a standard time-domain gating procedure was used to remove any spurious returns. Fig. 2 shows the reflectivity response of the single-layer knitted textile with the conducting diamond grid pattern. The response is typical of an inductive FSS and is strongly reflective at lower frequencies and non-reflecting (indicating transmission) at higher frequencies. Fig. 3 shows the reflectivity response of the single-layer knitted textile with the small triangular conducting patch pattern. The response is typical of a capacitive FSS and is transmissive at lower frequencies and reflecting at higher frequencies.

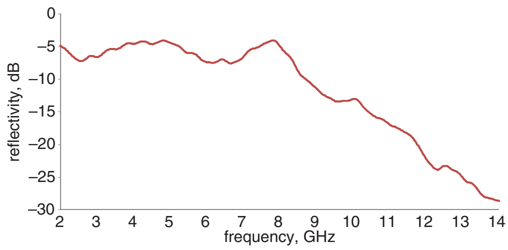

Fig. 2 *Reflectivity response of conducting grid knitted FSS measured at normal incidence*

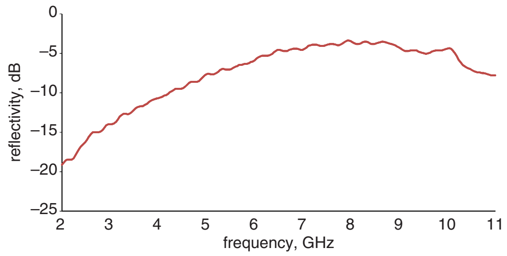

Fig. 3 *Reflectivity response of conducting patch knitted FSS measured at normal incidence*

Conclusions: Two experimental frequency selective surfaces, knitted from conducting yarn on a computerised flat-bed knitting machine, have been presented. The two knitted FSSs were configured for lowpass and highpass operation, respectively. Measured data shows that the knitted textile FSSs exhibit the fundamental characteristics of capacitive and inductive FSS designs. No simulated data is presented in this Letter as, of yet, we do not have any accurate models to describe the highly complex interactions and contact processes between the individual conducting yarns in the knitted structure (particularly at microwave frequencies), this being an area for future research. Other microwave components have been fabricated using the flat-bed knitting process, including 3D structures, and these will be reported at a later date.

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

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