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Integrated Embedded Frequency Selective Surface Sensors for Structural Health Monitoring

by

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16. Abstract The objective of this project is to design an embedded sensor element capable of characterizing mechanical properties including shear strain. This element will be designed using a Frequency Selective Surface (FSS) approach, and will be intended for integration into composite materials. The sensitivity of such FSS-based sensors to mechanical properties such as strain has been demonstrated by others [1-8]. As such, this work primarily focused on the development of FSS sensors that are specifically designed to be sensitive to shear strain.		14. Sponsoring Agency Code	
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1.0 Project Objective

The objective of this project is to design an embedded sensor element capable of characterizing mechanical properties including shear strain. This element will be designed using a Frequency Selective Surface (FSS) approach, and will be intended for integration into composite materials. The sensitivity of such FSS-based sensors to mechanical properties such as strain has been demonstrated by others [1-8]. As such, this work primarily focused on the development of FSS sensors that are specifically designed to be sensitive to shear strain.

2.0 Frequency Selective Surfaces

A Frequency Selective Surface is a periodic structure (in one or more dimensions) consisting of numerous FSS elements that are repeated and oriented in a particular manner on a substrate material. The substrate may or may not include a ground plane (a conductive materials, typically copper) on the opposite (back) side of the FSS substrate. There are a wide variety of well-known FSS elements, some of which are shown below in Fig. 1 [9].

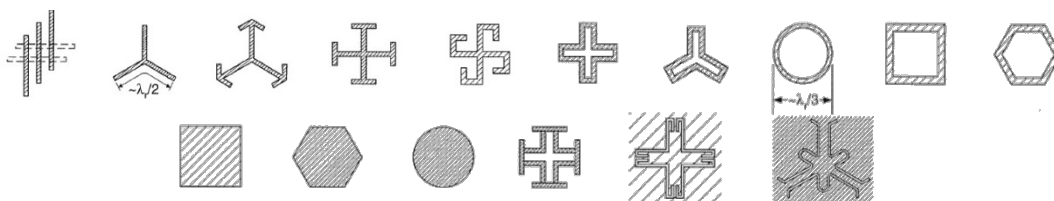


Fig. 1: Examples of different FSS elements [9].

Frequency Selective Surfaces have been studied intensively since the 1960's and have found application as spatial filters, reduction of radar cross section, and have also been incorporated into advanced antenna designs [9, 10]. Recently, FSS designs have been modified for operation in the THz, infrared (IR), and visible wavelengths [11].

2.1 FSS-Based Sensors

In general, FSS's have a specific electromagnetic response or signature when illuminated by an electromagnetic wave (for this investigation, a normally-incident planewave was considered). This signature may be reflection- and/or transmission-based, depending on whether or not the FSS was designed to include a ground plane. More specifically, if an FSS does include a ground plane, then the FSS will operate in reflection mode only (meaning the ratio of the reflected electromagnetic signal to the incident planewave, specified in dB, is the parameter of interest), as no electromagnetic energy will pass through the surface due to the ground plane. Alternatively, if the FSS design does not include a ground plane, then the response may be reflection and/or transmission-based (meaning the ratio of the transmitted electromagnetic signal to the incident

planewave, specified in dB, is the parameter of interest), as the potential for measuring either response exists.

In general, the reflection and transmission responses are commonly one or more sharp changes (i.e., resonant behavior including both resonant peaks and nulls) at a prescribed frequency (or frequencies). Since the FSS signature is highly dependent on the geometry of the FSS as well as the local material environment, changes in these parameters will impact the signature. It is also worth noting that the intended operation (e.g., reflection- or transmission-based) of the FSS may also have practical ramifications related to the ability to interrogate and measure the FSS response. For example, there may be applications that lend themselves well to a one-sided interrogation (meaning the FSS operates in reflection mode, and the interrogating and reflected signals are measured from the same location). As such, an FSS can be tailored to be sensitive to specific changes (per specific applications). In addition, it should be noted that in general, the electromagnetic response of any given FSS is a function of incident angle, and this sensitivity to incident angle is highly dependent on the individual design as well as the order of the resonance (often there exist multiple resonances, with the first resonant response being most insensitive to incident angle) [9].

The application of FSS-based sensors to structural health monitoring (SHM) is a relatively new approach. Recently, FSS methods have been applied to SHM to measure strain at microwave (X-band, 8-12 GHz) [2-6] and THz/IR frequencies [7, 8]. As such, this investigation extends this concept to include FSS-based sensors that are sensitive to shear strain.

To this end, the FSS element must be carefully designed such that its electromagnetic response is optimized for characterization of shear strain. Since FSS sensors can be designed to include the presence of ground plane, elements designed with and without a ground plane have been considered. With regards to practical application, the requirement (or lack thereof) of a ground plane may make this sensing approach easier to implement, especially for (multilayer) composite materials/structures.

3.0 FSS Simulations

All FFS elements considered in this investigation were printed on Rogers Duroid 5880 substrate. Further, all elements were designed to be resonant at 10 GHz (without mechanical loading). This frequency was selected due to ease of (future) laboratory measurements while keeping the element dimensions (inversely related to frequency) relatively small.

As the goal of this work was to investigate different FSS element designs with regard to their sensitivity to mechanical loading (in particular, shear strain), simulations were conducted in order to study the electromagnetic response of a set of FSS structures using ANSYS HFSS™, a full wave electromagnetic simulation software [9]. These simulations considered an infinite array of the specified element (e.g., creating a surface) under planewave illumination. In all cases, the reflection response of each FSS (both with and without mechanical loading) was determined from these simulations and is presented next. Due to the practical benefits of reflection-based FSS sensors (e.g., one-sided interrogation and measurement), transmission responses were not considered. As the electromagnetic response of an FSS is polarization dependent, both the co-polarized (referred to as co-pol herein) response (e.g., reflection response when the reflected and

incident signals are of the same polarization) and cross-polarized (referred to as cross-pol herein) response (e.g., reflection response when the reflected and incident signals are orthogonal) are considered. It has been shown in the literature [1-8] and through related investigations involving the PI/Co-PI team that when an FSS is mechanically loaded under strain, the co-pol response can be related to the amount of strain. However, the cross-pol response, especially as a tool for measuring shear strain, has not been investigated. This work builds on the potential of FSS sensors as a tool for measuring strain and investigates the sensitivity of the cross-pol response of the FSS when under (mechanical) shear strain. In order to model the mechanical/geometrical effect of shear strain, the dimensions of each element were mathematically modified to replicate the effect of an applied mechanical load. It is expected that when an FSS experiences shear strain, a cross-pol response will occur as a result of the “twisting” of the FSS, a manifestation that does not occur under (linear) strain. To this end, the co- and cross-pol responses of a set of FSS elements, with and without ground planes, are presented next.

3.1 Tripole Element

The first element considered is referred to as the tripole element and is shown in Fig. 2. In this case, the element included a ground plane. The tripole design was one of the first designs investigated, largely due to its common use within more traditional FSS applications. Its simplicity of design also made it a useful starting point for investigating FFS optimization. The co- and cross-pol responses of this FSS are shown in Fig. 3 for a range of shear strain (-4% – 4%) over an operating frequency range of 8-12 GHz (e.g., X-band). This range of shear strain is used for all elements studied in this investigation.

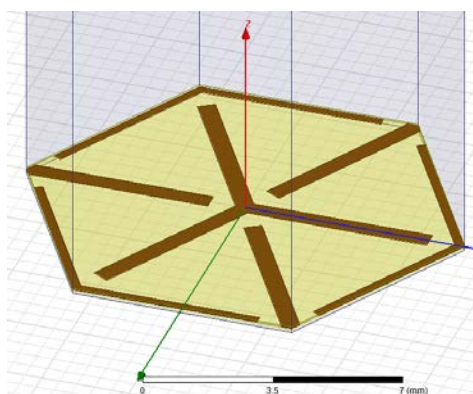


Fig. 2: Tripole element.

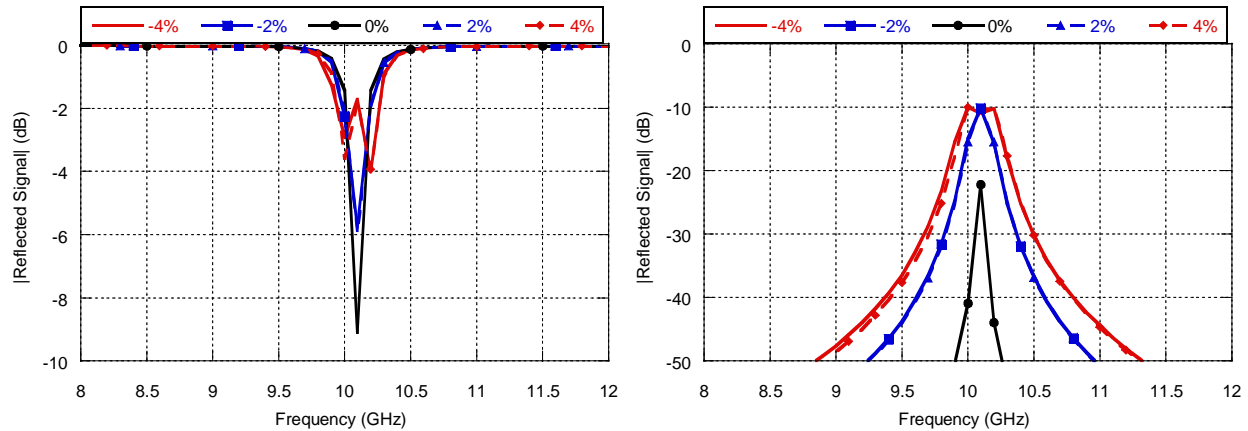


Fig. 3: Reflection response of tripole element with a ground plane – left, co-pol, and right, cross-pol.

As can be seen in Fig. 3, shear strain does not affect the resonant frequency (~ 10 GHz) for the co-pol response. However, the magnitude of the reflected signal is affected by shear strain. That is to say, when the FSS is unloaded (i.e., 0% shear), the reflected signal is near -10 dB (meaning a fairly small signal is reflected). However, as the shear strain is increased, the reflected signal increases, showing a sensitivity to shear. This may be useful practically, as the magnitude of the reflected signal may be monitored in order to provide an indication of shear strain. Moreover, for specific applications, a characteristic curve relating shear strain and the reflection response may be defined and used to determine when a critical applied strain threshold has been met or exceeded. It should also be noted that the reflection response for shear strain of $\pm 4\%$ indicates a split in resonance. This response may also be useful as an indication of shear strain; however the frequency range at which the split occurs is fairly small, meaning it may be difficult to detect this resonant split without requiring expensive measurement systems. Perhaps more importantly (as the sensitivity to shear strain is more significant) is the cross-pol response. More specifically, the cross-pol response, a resonant peak at ~ 10 GHz, is increased by nearly 15 dB once shear stress is applied to the FSS. This is quite significant, as the unsheared response of ~ -23 dB can be considered null (i.e., less than -20 dB) if using a basic measurement system, and an indication of strain may be detected if/when a signal is measured. Of course, further reduction in the unsheared cross-pol response would improve the performance of this FSS sensor design for detecting and quantifying shear strain. Another quantity that may provide an indication of shear is the quality factor, or Q-factor. The Q-factor provides an indication of the degree of resonance of a resonant structure and is defined as the ratio of the resonant frequency to the (3 dB) bandwidth (here, of the reflection response, but this definition is general and also valid for transmission responses as well). For the tripole element with a ground plane, the cross-pol Q-factor has a value of ~ 340 for the unsheared case, with a change of -253 and -57 as the shear strain is increased to $\pm 2\%$ and $\pm 4\%$, respectively. It should be noted that the negative change in Q-factor (in general) indicates that the Q-factor is reduced from the unsheared case as the element undergoes increasing shear strain.

Next, the same element design (tripole) was considered, but without the inclusion of a ground plane. The reflection response for this FSS is shown next in Fig. 4.

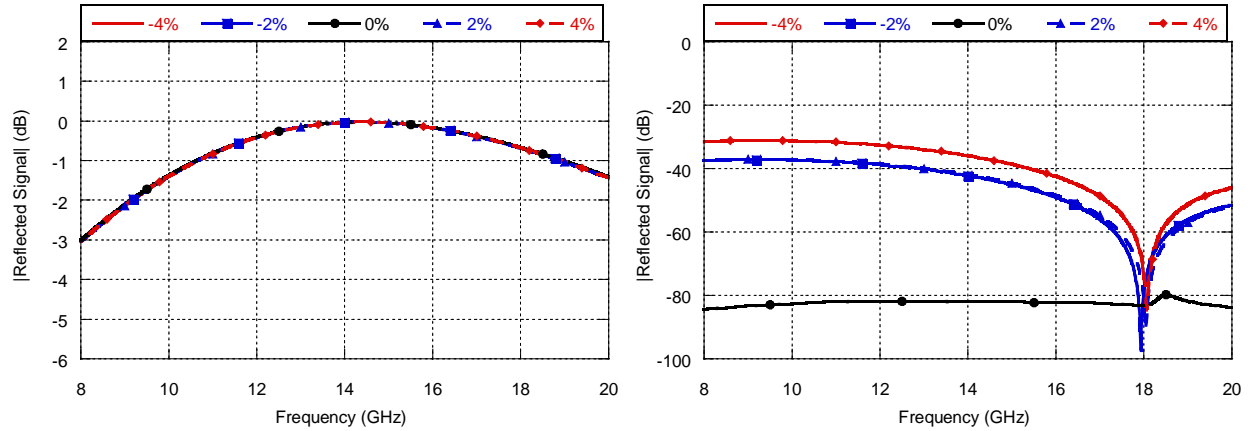


Fig. 4: Reflection response of tripole element without a ground plane - left, co-pol, and right, cross-pol.

As can be seen in Fig. 4, the co-pol response is quite different than that of shown in Fig. 3 (tripole FSS with ground plane). More specifically, the resonant frequency shifts to ~ 14 GHz (from 10 GHz above). In addition, the behavior at resonance is opposite to that of Fig. 3, meaning the resonant null now acts as a resonant peak. Further, the co-pol response is not sensitive to shear strain. A similar behavior can be seen in the cross-pol response (which is null for the unloaded case), where a wide resonant peak occurs at around 9 GHz when the FSS is under shear strain. As the shear strain increases, the reflection response also increases by ~ 5 dB (for an shear strain of $\pm 2\%$ to $\pm 4\%$). However, the response is still fairly low (below -30 dB), requiring more sensitive measurement systems in order to use this FSS design in practice. With regards to the Q-factor, since the resonant peak (in both the co- and cross-pol responses) is very wide (in frequency), the Q-factor is quite low and does not change appreciably as a function of shear strain. Nonetheless, this FSS design does have the benefit of an extremely low unsheared response (less than -80 dB, a value that is well below the noise floor of many measurement systems) with a significant increase as soon as shear is applied (-50 - -30 dB). While these values are still quite low, many measurement systems are capable of such measurements, making this element a potentially better design for sensing of shear strain. There is also a resonant null that occurs at ~ 18 GHz when the FSS is under shear strain, but as this null is quite low (and therefore unlikely to be detectable without a specialized (and costly) measurement system). This resonant null is also likely to be a function of the incident angle of the interrogating signal (as discussed above), resulting in additional measurement challenges should this element be used in practice. Furthermore, since the unsheared response at this frequency is quite similar, this resonant behavior is not useful for this investigation. However, the cross-pol response at frequencies less than ~ 16 GHz may be used to provide an indication of the presence of shear strain, as the difference between the unsheared case and $\pm 2\%$ shear strain is nearly 40 dB, with an additional change of ~ 10 dB with an additional $\pm 2\%$ shear strain (i.e., $\pm 4\%$ strain total). It should be noted that increasing the frequency range of the measurement system needed for practical application will also increase the cost of this sensing method, making an extended frequency measurement system less than ideal if a more narrowband solution can be obtained.

Overall, the tripole design with a ground plane provides a better response with regards to sensing of shear strain. However, due to the unsheared cross-pol response that exists for the tripole with

ground plane, this design is not considered optimal. To this end, the loaded tripole design (similar in geometry to that of Fig. 2) is considered next.

3.2 Loaded Tripole Element

The next element considered is referred to as the loaded tripole and is similar in geometry to that of Fig. 2 (tripole element), but is “loaded” with additions to the basic tripole shape, as shown in Fig. 5. The co- and cross-pol reflection response of the loaded tripole FSS with a ground plane is shown in Fig. 6 over an operating frequency range of 8-12 GHz.

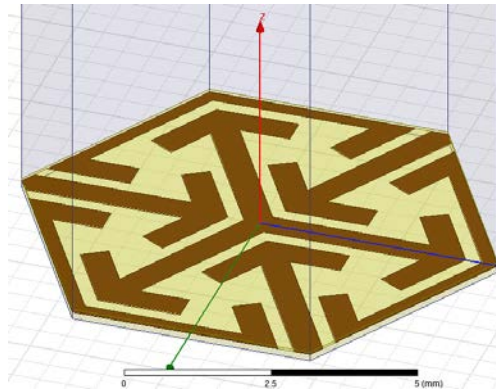


Fig. 5: Loaded tripole element.

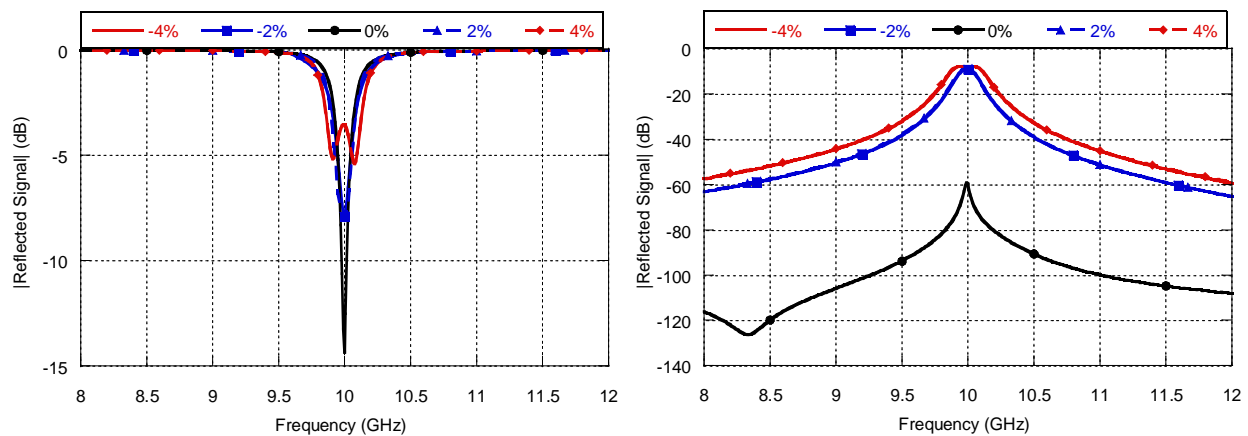


Fig. 6: Reflection response of loaded tripole element with a ground plane - left, co-pol, and right, cross-pol.

As can be seen in Fig. 6, the co-pol response at 10 GHz of the loaded tripole with a ground plane is similar to the unloaded tripole, but with a deeper resonant response (-10 to -15 dB for the loaded tripole as compared to -5 to -10 dB for the tripole). The resonant response for +/- 4% shear strain also exhibits the same “splitting” behavior as the tripole (above), a feature that may be useful as an indication of shear strain (assuming the measurement capability exists). However,

the effect of the loading (as compared to the tripole above) is more evident when the cross-pol response is considered.

The cross-pol response for the loaded tripole is improved from a practical standpoint (as compared to the tripole results of Fig. 3). More specifically, the cross-pol resonant peak (at 10 GHz) of the FSS, when under shear strain, is much larger (nearly -10 dB) and therefore more easily measured than the response of the FSS without shear strain (~ -60 dB, effectively null for many measurement systems). It is also interesting to note that this design is qualitatively sensitive to the presence of shear strain, rather than quantitatively sensitive. This can be seen in Fig. 6, as all responses for shear strain, regardless of the amount of shear strain, are quite similar. From a practical standpoint, this indicates that, when using such an FSS design for monitoring of shear strain, the cross-pol response may be observed until the response changes, thereby indicating the presence of shear strain. This may be beneficial if a simple “go or no-go” detection system is desired.

With regards to the Q-factor of the cross-pol response, as the shear strain is increased, the Q-factor decreases (as was seen for the tripole design discussed above). Thus, this change in Q-factor (-183 for 0 to +/-2% shear, and -30 for +/-2% to +/-4% shear) may be useful for quantitative monitoring of shear strain. Next, the reflection response of this FSS design without a ground plane is considered and is shown in Fig. 7.

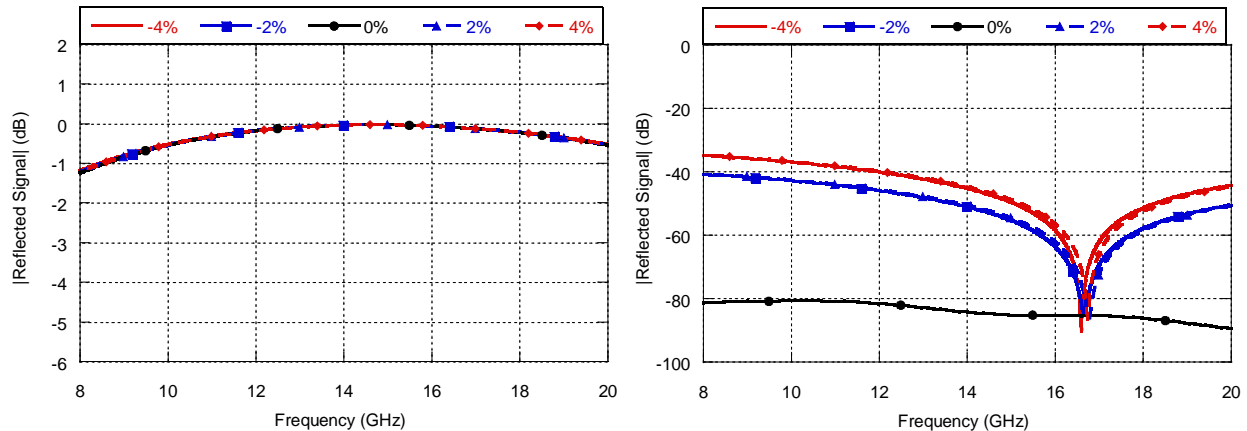


Fig. 7: Reflection response of loaded tripole element without a ground plane - left, co-pol, and right, cross-pol.

As can be seen in Fig. 7, the co-pol response of the loaded tripole without a ground plane is opposite of that of the loaded tripole with a ground plane (Fig. 6). That is to say, whereas the loaded tripole with a ground plane exhibited a sharp resonant null at 10 GHz, the same design without a ground plane exhibits a wide resonant peak at the same frequency. Further, this response is not sensitive to shear strain. Similar behavior can be seen in the cross-pol response, where above in Fig. 6, a resonant peak is observed, whereas here, a resonant null occurs at ~ 17 GHz. Further, the cross-pol response of the FSS design as a function of shear strain is different than that of the unsheared case; however, in all cases, the magnitude of the response is quite low, making practical detection a challenge. With regards to Q-factor, the Q-factor of the cross-pol response does show change as a function of shear strain, although comparing the Q-factor of a

strained to the unsheared case is not possible, as the unsheared case has (effectively) a Q-factor of 0, since the response is essentially flat as a function of frequency. In other words, the cross-pol response Q-factor of this element is not an ideal parameter for characterizing shear strain. Further, the Q-factor does not change as a function of shear strain.

The next FSS designs considered differ geometrically from the tripole and loaded tripole designs presented above. More specifically, the next designs incorporate a loop-based structure, whereas the tripole-based designs presented thus far feature a linear structure (i.e., no closed loop-based geometry).

3.3 Open Bent Cross

The next FSS element considered is referred to as the open bent cross design. This sensor design features a very dense interlocking geometry between elements, as shown below in Fig. 8. The reflection responses (co- and cross-pol) are shown in Fig. 9 for a frequency range of 8-20 GHz. The frequency range considered was increased for this element due to the unique element design and expected response. That is to say, this design was specifically considered as a potential design solution that would operate in a highly resonant manner (i.e. achieve sharp resonant peak or null responses) without the requirement of a ground plane while maintaining the lack of sensitivity to the angle of incidence of the interrogating signal. This design goal (lack of required ground plane) may be important in practice for shear sensing applications since an FSS sensor design that requires a ground plane may be difficult (or impossible) to embed in a preexisting structure. As such, the open bent cross design with a ground plane was not studied. Further, due to (expected) significant coupling between separate element arms, an additional goal of this FSS design was to achieve unique co-pol and cross-pol responses as a function of shear strain.

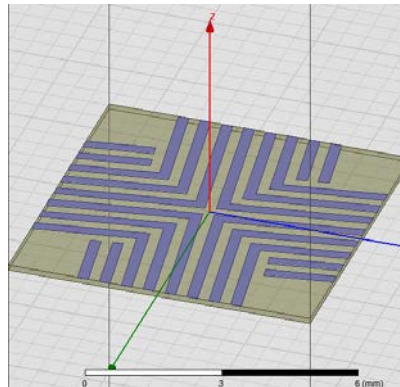


Fig. 8: Open bent cross element.

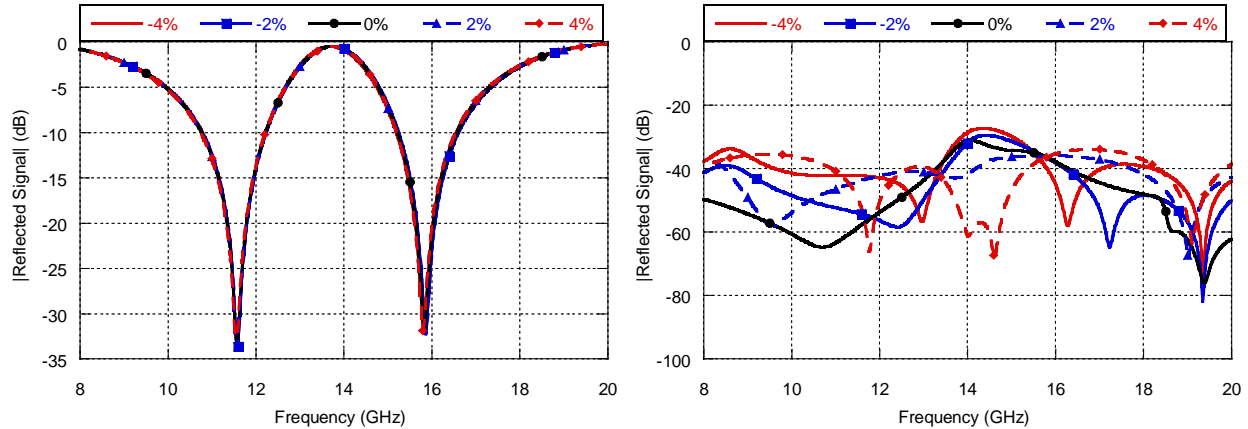


Fig. 9: Reflection response of open bent cross element without a ground plane - left, co-pol, and right, cross-pol.

As is evident in the co-pol response of Fig. 9, the intended (first) resonant frequency of 10 GHz was not achieved (due to the complexity of the element); rather, the resonant frequency for this element is 11.6 GHz. Unfortunately, this resonance is extremely insensitive to shear strain. A second resonance is evident at just below 16 GHz as well, but this resonance, while already a function of incident angle (a practical disadvantage), is also insensitive to shear strain.

The cross-pol response does change as a function of shear strain, but not in a useful manner. In other words, no trends in reflection response or Q-factor (as a function of shear strain) exist. This may be a result of the complex electromagnetic interactions, both within each element and between neighboring elements. As such, due to the irregular cross-pol response and lack of sensitivity of the co-pol response, this FSS design is not a good candidate for an FSS shear strain sensor.

3.4 Loaded Cross Loop Element

The next element design considered is referred to as the loaded cross loop, with the geometry shown in Fig. 10 and the co- and cross-pol responses for this design without a ground plane shown in Fig. 11, both over a frequency range of 8-20 GHz (in order to capture potentially useful responses that may occur at frequencies beyond X-band). It should be noted that the results for the loaded cross loop with a ground plane are not reported here as a result of poor performance (thereby rendering this design not useful for this investigation).

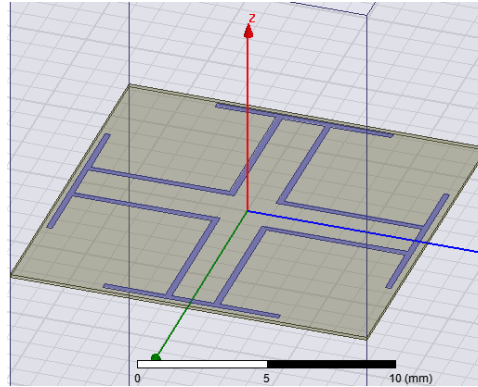


Fig. 10: Loaded cross loop element.

The cross loop design was considered after it was determined that that solid elements (elements that do not include loops such as the tripole and loaded triple) have a co-pol response that is largely unaffected by shear strain when not in the presence of a ground plane. By changing the element design to incorporate a loop, a multi-conductor transmission line effect may occur between the “arms” of the element (made up of separated wire strips). In this way, as the element is strained, the geometrical change between each arm (e.g., an effective multi-conductor transmission line) will change the electrical properties of the effective transmission line, thereby potentially causing the FSS response to be more sensitive to shear strain (e.g., geometric changes).

This intended sensitivity may be alternatively explained by considering the effective inductance and capacitance that is inherent to the element design. More specifically, a loop element will have a larger effective inductance than the “solid” elements shown above (tripole and loaded tripole). Further, elements that include a ground plane will also have a significant effect capacitance (caused by the element and nearby ground plane). In order to achieve an FSS response that is sensitive to shear strain, one or both of these parameters (inductance or capacitance) must be changed as the element undergoes shear strain. An additional point of note is that if the effective inductance and capacitance is changed by the same amount when under loading, the FSS response will be insensitive, as inductive and capacitive effects will cancel. Thus, by adding a strong inductance or capacitance inherent to the design, changes to these parameters will, by design, differ as a function of shear strain, thereby increasing the sensitivity of the FSS sensor design to this parameter.

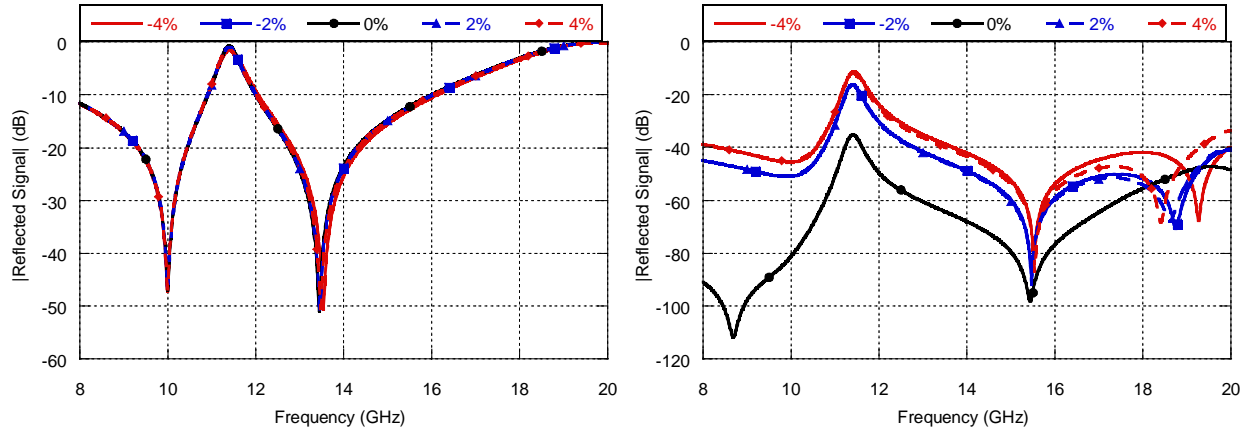


Fig. 11: Reflection response of loaded cross loop without a ground plane - left, co-pol, and right, cross-pol.

The co-pol response (consisting of two distinct resonant nulls at 10 and ~ 13.5 GHz) of this design does not show a sensitivity to shear strain (as has been the case with the above-discussed element designs as well). However, the cross-pol response features a distinct resonance peak at ~ 11 GHz. When unloaded, the cross-pol response is nearly -40 dB (a very small response that can be considered null for many practical measurement systems). However, as the shear strain increases, the cross-pol response also increases significantly; namely to ~ -20 dB for $\pm 2\%$ shear strain, and ~ -10 dB for $\pm 4\%$ shear strain. However, the Q-value for this element (38 for all cases) is not useful for detecting or characterizing shear strain, as the Q-value is not sensitive to changes in shear strain.

There is also a resonant null at ~ 15.5 GHz, but this characteristic is not useful since the response is very similar for the sheared and unsheared cases. In addition, this response will not be independent of the angle of incidence of the interrogating signal (an important consideration for practical application). As such, this sensor design is one of the best considered thus far (from a practical standpoint), as a ground plane is not required (making this design better suited for implementation), and the cross-pol response exhibits a measurable sensitivity to shear strain.

3.5 Cross Loop Element

A last element design considered is the cross loop element, shown in Fig. 12 (also for a frequency range of 8-20 GHz). The geometry of this element is quite similar to that of the loaded cross loop (see Fig. 10), but without the “loading” (e.g., the additional length added to the end of each arm of the cross loop). The co- and cross-pol results of this design without a ground plane are presented in Fig. 13. It should be noted that the results for the cross loop with a ground plane are not reported here due to poor performance, rendering this design not useful for this investigation.

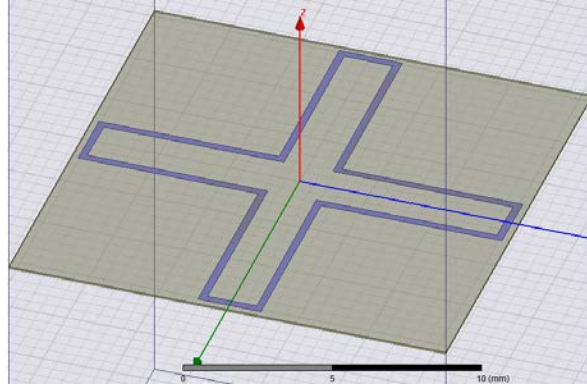


Fig. 12: Cross loop element.

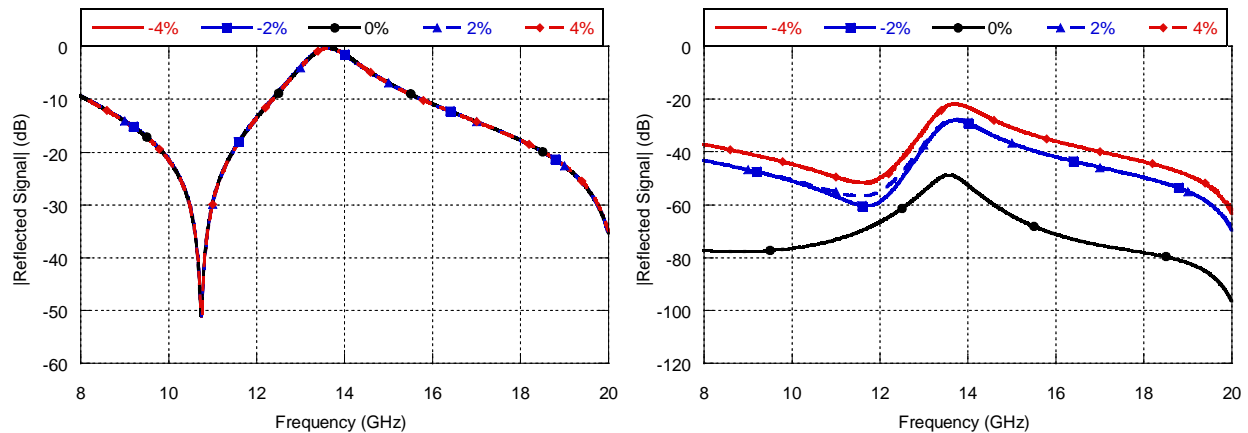


Fig. 13: Reflection response of cross loop without a ground plane - left, co-pol, and right, cross-pol.

As can be seen in Fig. 13, while a distinct co-pol resonant null is evident at ~ 11 GHz, the co-pol response of this design is not sensitive to shear strain (as was the case for the loaded cross loop above). Additionally, when comparing the co-pol response here to that of the loaded cross loop (Fig. 11), a similar response as a function of frequency can also be seen, although the second resonance occurs at a higher frequency (beyond 20 GHz for the cross loop of Fig. 13, while the loaded cross loop of Fig. 11 has a second resonance at ~ 13.5 GHz).

The cross-pol response for the unloaded design is also very similar to that of the loaded design (Fig. 11), again with the frequency of the resonant peak shifted in frequency (to ~ 13.5 GHz). This response is sensitive to shear strain, with a change of ~ 30 dB from an unsheared case to a shear strain of $\pm 2\%$, and an additional change of ~ 10 dB from $\pm 2\%$ to $\pm 4\%$ shear strain. Moreover, the magnitude of the reflection response is lower than that of the loaded cross loop (see Fig. 11), possibly making this design less optimal from a practical measurement perspective.

In addition, a second cross-pol resonant null occurs outside of the frequency range considered for this design (e.g., beyond 20 GHz), as the beginning of that null can be seen in Fig. 13. Of course, for practical implementation, higher frequencies can be considered in order to capture the second

resonant response, but at the cost of more complicated (e.g., wide-band) measurement equipment (along with a sensitivity to incident angle of the interrogating signal). Lastly, as was the case with the loaded cross loop, the Q-factor does not exhibit sensitivity to shear strain and therefore is not a useful parameter to consider for this FSS sensor design.

3.6 FSS Element Summary

As shown above, the FSS response (i.e., co- and cross-pol resonant peaks and nulls, along with Q-factor), as well as its' sensitivity to shear strain, varies greatly as a function of the particular FSS element geometry. In general, the co-pol response is not sensitive to shear strain. However, the cross-pol response, in general, has been shown to change as a function of shear strain, although the specific response differs greatly the particular FSS element design. To summarize the elements considered in this work, Tables I-III below are provided. More specifically, Table I summarizes the unloaded/unsheared FSS reflection responses (e.g., resonant frequency and magnitude of the resonant response) for both the co- and cross-pol responses. Table II summarizes the change in cross-pol resonant response of the elements considered above as a function of shear strain, and Table III summarizes the Q-factors of the co- and cross-pol responses (of the above elements) and change in cross-pol Q-factor as a function of shear strain.

Table I: Summary of unloaded/unsheared FSS reflection responses.

	Co-Pol		Cross-Pol	
	Res. Freq. (GHz)	Resonant Magnitude (dB)	Optimal Freq. (GHz)	Resonant Depth (dB)
Grounded Tripole	10.1	-9.1	10.1	-10.9
Ungrounded Tripole	14.4	0	9.3	-31.1
Grounded Loaded Tripole	10	-14.4	10	-7.9
Ungrounded Loaded Tripole	14.7	0	5.7	-33.8
Ungrounded Open Bent Cross	11.6	-33.9	3.6	-31
Ungrounded Loaded Cross Loop	10	-47.2	11.4	-11.4
Ungrounded Cross Loop	10.8	-51.3	13.7	-21.8

Table II: Change in cross-pol FSS resonant response to shear strain.

	Δ -Response to Shear Strain (dB)	
	Shear Strain (0 to +/-2%)	Shear Strain (+/-2% to +/-4%)
Grounded Tripole	12.1	0.9
Ungrounded Tripole	45.8	6.2
Grounded Loaded Tripole	50.9	1.1
Ungrounded Loaded Tripole	43.2	5.9
Ungrounded Open Bent Cross	15.1	3.8
Ungrounded Loaded Cross Loop	19.1	4.8
Ungrounded Cross Loop	21.7	5.8

Table III: Summary of Q-factors of FSS co- and cross-pol responses and change in cross-pol Q-factor as a function of shear strain.

	Co-Pol Q-factor	Cross-Pol Q-factor	Cross-Pol Δ -Q	
			Shear Strain (0 to +/-2%)	Shear Strain (+/-2% to +/-4%)
Grounded Tripole	129.2	343.5	-253.1	-56.8
Ungrounded Tripole	1.1	1.3	-0.1	0
Grounded Loaded Tripole	312	250	-183.4	-30.2
Ungrounded Loaded Tripole	0.8	1.2	N/A	0
Ungrounded Open Bent Cross	128.7	N/A	N/A	N/A
Ungrounded Loaded Cross Loop	200	38	0	0
Ungrounded Cross Loop	250	18.3	-2.8	0.1

Overall, of the FSS element designs considered in this investigation, the FSS design including a ground plane that performed best is the loaded tripole. While the tripole with a ground plane also exhibited a similar resonant response, the magnitude of the cross-pol reflection response under shear loading is higher (e.g., more power is reflected back, making this response more ideal from a measurement detection point-of-view). Additionally, the change in cross-pol reflection response from +/- 2 to +/- 4% shear strain is also greater for this particular element design. It

should be noted that the co-pol response is not considered for determining optimal element designs, as the co-pol response, in general, is not sensitive to shear strain.

Thus far, Q-factor of the elements considered with a ground plane (tripole and loaded tripole) has shown the most success as a second parameter that may be used to detect and characterize shear strain. The Q-factor of the elements without a ground plane is much less sensitive; a result of the “less resonant” cross-pol response seen in the element geometries considered.

The best element without a ground plane of the elements considered is the cross loop (both loaded and unloaded, as the performance of both elements is similar) The unloaded cross loop has more significant shifts in cross-pol reflection response as a function of shear strain, but the magnitude of the response (especially for higher shear strain) is not as large. The loaded cross loop exhibits a higher magnitude of the cross-pol reflection response for larger shear strain (e.g., +/- 4%), but there is less difference as a function of shear strain, along with the fact that the unsheared response is nearly -50 dB (representing a fairly low-power response to begin with that may be more challenging to detect). Ultimately, the results presented here show that FSS sensors have strong potential for sensing and characterizing shear strain, and that specialized design must be incorporated in order to arrive at an optimal sensor per each application.

4.0 Additional FSS Modeling

In order to gain a more rigorous understanding of the electromagnetic interaction between FSS elements of a given FSS, a fundamental study (beyond the scope of this work) was conducted. Since an FSS is comprised of a periodic set of elements arranged in a particular manner, the electromagnetic interaction within and between elements can be modeled using circuit elements [13]. Thus, the purpose of this study was to develop such a circuit model that incorporates resistive, inductive, and capacitive elements to represent these electromagnetic interactions. Such a model will be specific to a given FSS geometry, and is based primarily on inductive and capacitive elements (representing energy storage and resonant behavior, rather than resistive elements that represent energy loss). The elements for a given model are based on the metallic strip grid array impedance equations developed by Marcovitz in [14].

Generally speaking, the model is designed (for a given FSS) by estimating which portions of the FSS element will self-resonate, and which portions will interact with adjacent elements within the surface. These relationships may then be described using the array impedance equations of [14] in a way that is directly related to the element dimensions (and geometry). A model of this type is especially important to FSS design, as it provides a more fundamental and intuitive understanding of the functionality of a given FSS, and may also prove useful in FSS synthesis, in order to create an FSS that produces a desired electromagnetic response. To this end and as was investigated in [13], a preliminary circuit model was developed for an FSS element known as the Jerusalem cross, shown below in Fig. 14.

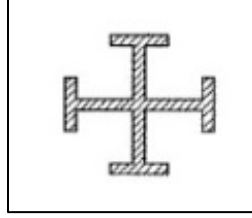


Fig. 14: Jerusalem cross element considered for preliminary modeling effort [9].

The Jerusalem cross element (without a ground plane) was considered initially for the circuit model development because it is a well-known (and well understood) FSS element, making it an ideal candidate for advanced modeling. Shown below in Fig. 15 are the simulated reflection and transmission responses for this element as determined by the circuit element model.

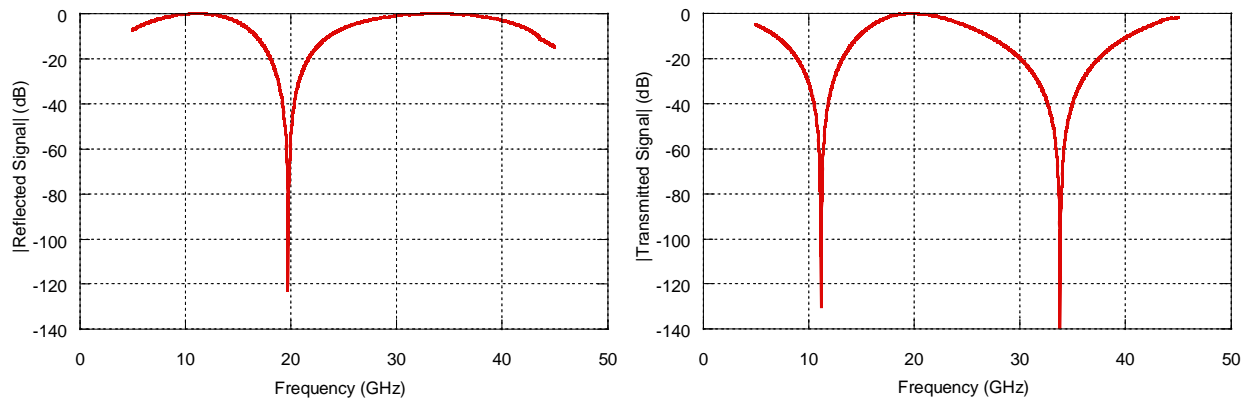


Fig. 15: Simulated reflection and transmission responses from developed model.

As was mentioned above, a similar investigation was reported in [13], providing a method by which this model can be verified. As shown below in Table IV, the results (i.e., reflection and transmission response) model developed for this work match well with that reported in [13].

Table IV: Resonant frequencies for Jerusalem cross circuit model and those of [13].

	Reflection Resonant Frequency	Transmission Resonant Frequency (1 st and 2 nd nulls)
Reference [13]	19.8 GHz	11.3 GHz, 34.2 GHz
Developed Model	19.76 GHz	11.17 GHz, 33.83 GHz

This circuit model (and the approach taken to develop the model) will be extended in future works to predict reflection and/or transmission responses of more complicated (and potentially

novel) FSS designs, including those presented above, in order to assist in creating a particular desired FSS response (e.g., FSS synthesis), such as that needed for shear strain sensing.

5.0 Concluding Remarks

As the purpose of this investigation was to design an embedded sensor element capable of characterizing mechanical properties including shear strain, the focus of the work presented here and summarized in Tables I-III was sensitivity to shear strain. To this end, the results show that overall, the FSS co- and cross-pol response and subsequent sensitivity to shear strain varies greatly as a function of FSS element geometry. Further, it has been shown that the co-pol response is not sensitive to shear strain, but the cross-pol response does exhibit this sensitivity. The Q-factor is another parameter that may be useful for such a sensing goal. A more detailed discussion on the performance characteristics of the FSS element designs considered as part of this work is provided above in Section 3.6

5.1 Future Work

At the time of this report preparation, an FSS sensor, based on the elements studied in this investigation, is being designed for fabrication and implementation into a simple composite structure. This FSS sensor will be fabricated in conjunction with colleagues at Missouri University of Science and Technology, and will be tested in the laboratory for sensitivity to strain and shear strain. Further study may also include development of such sensors for materials characterization purposes, including detection of disbonds, delamination, and other damage in layered structures.

Related to this, the preliminary circuit model discussed above will also be further developed and extended to permit specialized and tailored FSS responses (e.g., improved sensitivity to shear strain).

5.2 Project Deliverables

The project deliverables (outside of the Final Report) for this award focused on publications (specifically, submission of a journal paper to a suitable, peer-reviewed journal). At the time of this report preparation, a conference proceedings paper is in preparation (submission date Sept. 2014) for submission to the IEEE Instrumentation and Measurement Society International Instrumentation and Measurement Technology Conference (I2MTC) 2015. Additional publications will result after submission of the final report.

Related to this, two proposals have been submitted as a result of this Grant; one to the National Science Foundation and one to the American Society of Nondestructive Testing (ASNT). The proposal submitted to ASNT was submitted to their Graduate Fellowship program and was funded. This funding will support the graduate student working on this project beginning August 2014.

5.3 Publications and Student Support

The following publications and presentations have resulted from this Grant:

1. Pieper, D. and K.M. Donnell, "Delamination Detection Using Frequency Selective Surfaces", *Missouri University of Science and Technology Chancellor's Fellowship Presentation*, Feb. 24th, 2014, Rolla, MO.

Additionally, the following students have been supported on this Grant:

1. Mr. Dustin Pieper, MSEE student, Applied Microwave Nondestructive Testing Laboratory (*amntl*), Department of Electrical and Computer Engineering, Missouri University of Science and Technology.
2. Mr. Thomas Roth, Undergraduate EE student, Applied Microwave Nondestructive Testing Laboratory (*amntl*), Department of Electrical and Computer Engineering, Missouri University of Science and Technology.

Related to this work, Mr. Thomas Roth also completed an Honors research project on a related topic which provided him the opportunity to work with Mr. Pieper (the graduate student on the grant) on independent yet related research.

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