เอกสารอ้างอิง

[1] S. Pranonsatit, A.S. Holmes, I. D. Robertson and S. Lucyszyn, "Single-pole eight-throw RF MEMS rotary switch", *Journal of Microelectromechanical systems*, vol. 15, no. 6, pp. 1735-1744, Dec. 2006.

[2] C. Zhang, M. Kuhn, M. Mahfouz and A. E. Fathy, "Planar antipodal Vivaldi antenna array configuration for low cross-polarization and reduced mutual coupling performance", in *IEEE Antennas and Propagation Society International Symposium*, Honolulu, HI, pp. 725-728, 2007.

[3] L. Ying and C. Ai-Xin, "Design and application of Vivaldi antenna array", in *International Symposium on Antennas, Propagation and EM Theory*, Kunming, China, pp. 267-270, 2008.

[4] K. Van Caekenberghe and T. Vaha-Heikkila, "An analog RF MEMS slotline true-time-delay phase shifter", *IEEE Transactions on Microwave Theory and Techniques*, Scottsdale, AZ, pp. 2151-2159, 2008.

[5] J. C. Rock, T. Hudson, B. Wolfson, D. Lawrence, B. Pillans, A. R. Brown and L. Coryell, "A MEMS-based, Ka-band, 16-element sub-array", in *IEEE Aerospace conference*, Big Sky, MT, pp. 1-11, 2009.

[6] K. S. Yngvesson, T. L. Korzeniowski, Y.–S. Kim, E. L. Kollberg and J. F. Johansson, "The tapered slot antenna – a new integrated element for millimeter-wave applications", *IEEE Transactions on Microwave Theory and Techniques*, vol. 37, no. 2, pp. 365-374, Feb. 1989.

[7] T. Thungren, E. L. Kollberg and K. S. Yngvesson, "Vivaldi antennas for single beam integrated receivers," in *European Microwave Conference*, Helsinki, Finland, pp. 361-366, 1982.

[8] R. O. Lee and R.N. Simons, "Effect of curvature on tapered slot antennas", in *Antennas and Propagation Society International Symposium*, Baltimore, MD, pp.188-191, 1996

[9] J. Shin and D. H. Schaubert, "A parameter study of stripline-fed Vivaldi notch-antenna arrays", *IEEE Transactions on Antennas and Propagation*, vol. 47, no. 5, pp. 879-886, May 1999.

[10] S. J. Orfanidis. (2009, Nov.). *Electromagnetic Waves and Antennas, Chapter 18 Aperture Antennas* [Online]. Available: http://www.ece.rutgers.edu/~orfanidi/ewa/

7. ภาคผนวก

Output จากโครงการวิจัยที่ได้รับทุนจาก สกว.

1. ผลงานตีพิมพ์ในวารสารวิชาการนานาชาติ (ระบุชื่อผู้แต่ง ชื่อเรื่อง ชื่อวารสาร ปี เล่มที่ เลขที่ และหน้า) หรือผลงานตามที่คาดไว้ในสัญญาโครงการ
2. การนำผลงานวิจัยไปใช้ประโยชน์
   - เชิงพาณิชย์ (มีการนำไปผลิต/ขาย/ก่อให้เกิดรายได้ หรือมีการนำไปประยุกต์ใช้โดยภาคธุรกิจ/บุคคลทั่วไป)
   - เชิงนโยบาย (มีการกำหนดนโยบายอิงงานวิจัย/เกิดมาตรการใหม่/เปลี่ยนแปลงระเบียบข้อบังคับหรือวิธีทำงาน)
   - เชิงสาธารณะ (มีเครือข่ายความร่วมมือ/สร้างกระแสความสนใจในวงกว้าง)
   - เชิงวิชาการ (มีการพัฒนาการเรียนการสอน/สร้างนักวิจัยใหม่)
3. อื่นๆ (เช่น ผลงานตีพิมพ์ในวารสารวิชาการในประเทศ การเสนอผลงานในที่ประชุมวิชาการ หนังสือ การจดสิทธิบัตร)

Output จากการดำเนินโครงการวิจัยสายอากาศแบบหมุนในระบบเครื่องจักรกลไฟฟ้าจุลภาคย่านความถี่วิทยุ (MRG5180264) ได้แก่

2. การนำผลงานวิจัยไปใช้ประโยชน์
   - เชิงสาธารณะ (มีเครือข่ายความร่วมมือ/สร้างกระแสความสนใจในวงกว้าง)
   - เชิงวิชาการ (มีการพัฒนาการเรียนการสอน/สร้างนักวิจัยใหม่)
3. อื่นๆ (เช่น ผลงานตีพิมพ์ในวารสารวิชาการในประเทศ การเสนอผลงานในที่ประชุมวิชาการ หนังสือ การจดสิทธิบัตร)

อันจะเห็นได้จากการที่ได้มีโอกาสแลกเปลี่ยนผลงานต่อนักวิจัย สกว. ท่านอื่น ซึ่งทำให้นักวิจัยได้รู้จักเทคโนโลยี RF MEMS อันสามารถที่จะทำให้เกิดเป็นความร่วมมือในงานวิจัยอื่นๆต่อไปได้ นอกจากนี้ยังสามารถใช้ผลที่ได้จากการดำเนินโครงการเป็นหัวข้อสำหรับโครงการวิจัยอื่นๆต่อไปได้ เช่นการตรวจสอบการประมวลผลจากแบบจำลองสามมิติ หรือการออกแบบสายอากาศที่ลดการคู่ควบ เป็นต้น

นอกจากนี้ยังได้มีการเสนอผลงานในการประชุมวิชาการนานาชาติ ดังนี้

S. Pranonsatit, A. S. Holmes and S. Lucyszyn, "Sectorised horn antenna array using an RF MEMS rotary switch," to be published in *Asia-Pacific Microwave Conference (APMC 2010)*, Yokohama, Japan, Dec. 2010.

Sectorised Horn Antenna Array Using an RF MEMS Rotary Switch

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Abstract — **A sectorised horn antenna array, employing a single-pole multiple-throw RF MEMS rotary switch, has been demonstrated for the first time. Preliminary measurements from the first ever experimental proof-of-concept prototype demonstrator confirm the principle of operation for this novel antenna array. It is believe that with further work a much higher performance can be achieved.**

Index Terms — **Sectorised antenna array, horn antenna, RF MEMS, rotary switch.**

I. Introduction

Radio frequency microelectromechanical systems (RF MEMS) technology can offer unprecedented performance over solid-state devices (e.g. switches and varactor diodes), in terms of factors that can include performance figure-of-merit and RF power nonlinearity [1]. There are a number of notable examples of antennas that employ RF MEMS devices. These can be divided into two distinct categories: *generic RF MEMS antennas* and *RF MEMS antenna circuits*. The former has its radiating elements that physically move under some form of actuation mechanism; while the latter has fixed position radiating elements that employ RF MEMS switches or variable capacitors to alter the electrical behaviour of the radiating elements [1].

The first generic RF MEMS antenna was reported just over a decade ago by Chiao *et al.* [2, 3]. Here, the arms of a Vee-antenna are independently controlled using linear scratch drive actuators. As a result, the azimuth pointing direction and directivity of the main beam can be controlled independently. More recently, a V-band single-platform beam steering transmitter [4] was demonstrated by employing an antenna having two degree of rotational freedom around torsion bar hinges, with the use of an external magnetic force [5, 6].

There are many examples of RF MEMS antenna circuits. Multi-band operation has been demonstrated using RF MEMS switches within fractal antennas [6]. The strategic placement of switches can control the currents in the branches of the antenna. This affects the resonance behaviour of the entire antenna and its radiation pattern. For example, using a Sierpinski Gasket design, a reconfigurable antenna was demonstrated [7]. More recently, a much simpler dual-frequency reconfigurable slot dipole array for X- and Ka-band [8] and Ka- and V-band [9] were reported by placing RF MEMS switches across the slots. Similarly, a single-arm spiral antenna with RF MEMS switches located along the line was reported for X-band operation [10].

Thermo-compression wafer bonding techniques have also been employed to realize a 3-layer tuneable coplanar patch antenna (TCPA) with RF MEMS varactor [11-12]. Also, a 35 GHz coupled patch antenna array had been demonstrated within a multi-layer LTCC module [13]. Here, flip-chip mounted RF MEMS phase shifter chips were integrated between the feed network and a serially fed patch antenna array, to implement 1D beam steering. Moreover, wafer bonding by cross linking SU8 was realized in a MEMS programmable lens-array (MPLA) antenna [14].

In addition, at X-band, a 4 x 8 patch antenna array was realized on a Teflon substrate, with a hybrid integration of silicon RF MEMS phase shifters for performing beam steering [15]. The same team then went on to demonstrate a data link at Ka-band, with the RF MEMS phase shifter chips placed within 3-layer LTCC cavities [16].

The Vivaldi antenna is an end-fired tapered slot antenna (TSA) [17]. The slot is smoothly tapered from narrow to wide ends, to give it an ultra-wideband (UWB) performance [18]. Vivaldi antennas generally exhibit high gain and linearly polarization. Compared to other UWB solutions, Vivaldi antennas benefit from compactness, simplicity and an adjustable beamwidth. Since 1974 [19], various Vivaldi antenna designs have been reported [20-28]. Moreover, the issue of mutual coupling effects on bandwidth in Vivaldi antenna array has also been investigated [29-30]. While it is believed that mutual coupling can improved bandwidth, when compared to an isolated Vivaldi element [31], it has been shown that mutual coupling has a negative effect on bandwidth; although this can be improved by including chokes that attenuate currents between elements.

Vivaldi antennas have already been used with RF MEMS. Examples include a 10 GHz analog slotline true time delay (TTD) phase shifter [32], an UWB near-field imaging system [33] and a 16-element phased sub-array with Ka band phase shifters [34].

Single-pole multiple-throw switches have been realized by integrating a number of single-pole single-throw (SPST) switches. However, as the number of bits increases, this solution can result in yield and reliability issues. For example, a discrete single-pole eight-throw (SP8T) switch may require about 15 times the amount of real estate and has 8 separate moving parts, when compared to our SP8T rotary switch that only has one moving part. [35]. This switch has already been demonstrated within a 2-bit digital TTD phase shifter application [36].

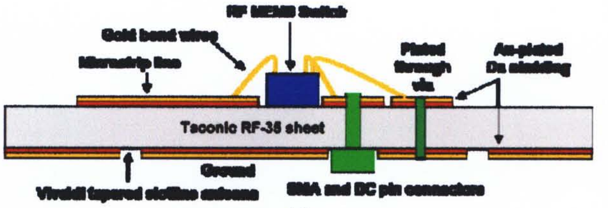
In this paper, an X-band sectorised horn antenna array is described that incorporates eight Vivaldi antennas with a central SP8T RF MEMS rotary switch. The design, fabrication and measured performance of this unique RF MEMS antenna are described for the first time.

II. ANTENNA DESIGNS AND FABRICATION

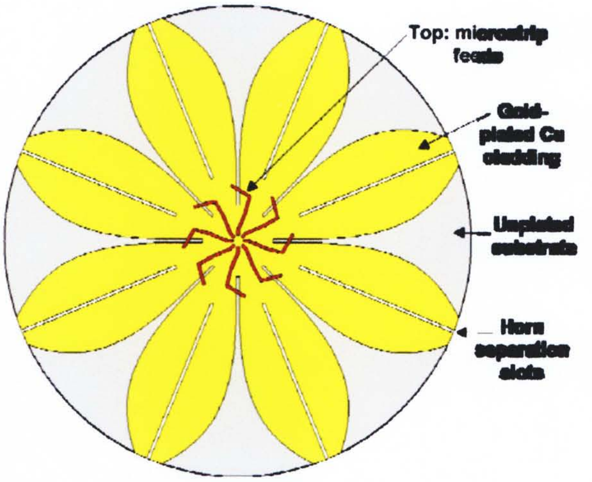
The antenna is composed of two substrates. The SP8T RF MEMS switch was fabricated on a 500 μm thick quartz substrate, having gold and nickel metallization layers; while the Vivaldi antenna structure was made using the 250 μm thick Taconic RF-35 laminate, as illustrated in Fig. 1.

The RF MEMS rotary switch consists of two components: stator and rotor. By employing the wobble motor principle, the centre of the rotor is raised above the stator and is attracted downward, due to the electrostatic potential applied to the stator's dc electrodes underneath [35]. The rotor can be made to perform a precessional motion, in which the physical contact between rotor and stator rotates continuously around the periphery of the device. For RF switching, the stator has one input and eight output CPW transmission lines around the perimeter of the rotor. On the SP8T switch, the input RF signal is fed via the input CPW line, which extends underneath the rotor, to make electrical contact with the bearing/axle of the stator. The signal then makes its way onto the rotor, via the inherent rotating physical/ohmic contact between the touching surfaces of the bearing and the tilted rotor. The signal is then transferred to the selected output line at the outer edge of the tilted rotor, where the physical contact with the stator is made. The switching function is made by selectively actuating one of eight independent dc bias electrodes, to hold the rotor at one of eight stable equilibrium positions, so as for the rotor to make ohmic contact with the corresponding CPW output line on the stator. Bonded wires interconnects are employed between the switch's CPW output lines and the Taconic RF-35 laminate's microstrip lines, as illustrated in Fig. 1(a). The RF signal from microstrip lines are then coupled to the associated slotline beneath, which is then radiated via the tapered slots of the Vivaldi antennas, as shown in Fig. 1(b). The individual Vivaldi antennas were housed in their own pyramidal horn, in order to greatly increase directivity. As a result, horn separation slots were introduced into the RF-35 laminate, as illustrated in Fig. 1(b).

It can be seen in Fig. 1(a) how the main RF input signal is fed to the SP8T switch via an SMA connector underneath the Taconic RF-35 laminate and bond wires above. The dc bias pin connectors were connected in a similar way as the SMA connector. Ground connections between the antenna and the CPW-to-microstrip transition were with plated-through vias.



(a)



(b)

Fig. 1. Substrate parts of complete antenna array (not to scale): (a) integration of switch and Vivaldi antenna and (b) Taconic RF-35 laminate.

In designing the antenna, the value for the effective thickness of the substrate, normalized to the free space wavelength at centre frequency, should be within the optimal range given by (1) [24]:

$$0.005 \le \frac{\left(\sqrt{\varepsilon_r} - 1\right) t}{\lambda_0} \le 0.03 \qquad (1)$$

where ε_r and t are the dielectric constant and physical thickness of the radiating substrate, respectively, and λ_0 is the free-space wavelength at the centre frequency of operation. The beam width will be too wide on thinner substrates, whereas the main beam will break up for thicker substrates.

It can be seen from Fig. 1(b) that the Taconic RF-35 laminate substrate has a circular shape; with a 30 cm diameter, 250 μm physical thickness and covered with an 18 μm thick electrodeposited Cu cladding on each side (plated with 0.5 μm thick gold). The dielectric constant and $tan\delta$ are 3.5 and 18 x 10^{-4}, respectively. Therefore, at a center frequency of 10 GHz, the normalized effective thickness for this Taconic RF-35 laminate is 0.0073, which is within the optimum range. The effective radiating length of the antenna is $5\lambda_0$, i.e. within the recommended range of 2 to 12 λ_0 [37].

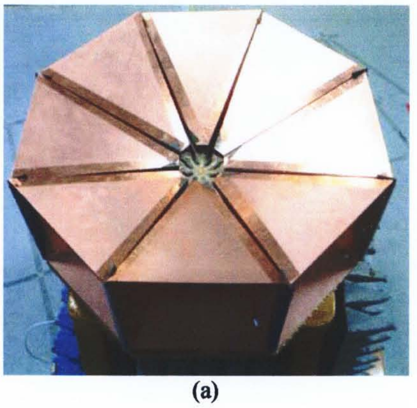
The overall size of the antenna is limited by the diameter of RF-35 laminate sheet. In our case, all eight Vivaldi antennas had to fit onto a 30 cm diameter sheet. Each antenna occupies a 45° slice of the circle. The dimensions of the microstrip line and slotline feeds were calculated using Agilent's LineCalc. The curvature of the tapered slotline follows an exponential profile [25, 38], defined by the following:

$$y = 0.5e^{0.04x} \tag{2}$$

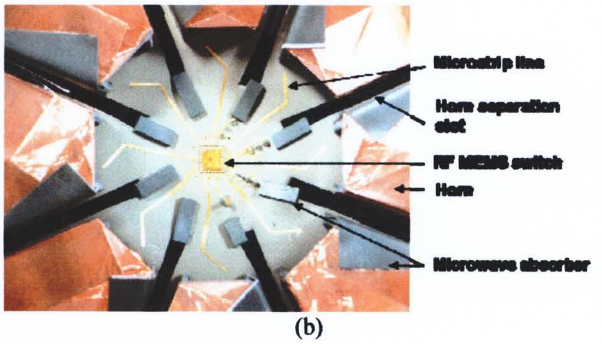
where x is the length and y is the width of the slotline.

This curvature results in the opening flare (in the y-axis) of 36°. This optimized angle is constrained by the width of the antenna's aperture and the degree of curvature. The latter determines the performance of the antenna. Specifically, when the degree of curvature is increased, the beamwidth is also increased but the bandwidth and return loss are reduced [38].

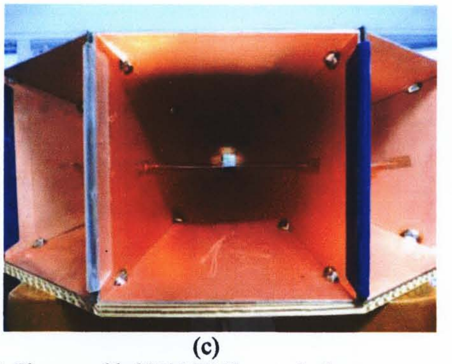
The assembled sectorised horn antenna array is shown in Fig. 2. Fig. 2(a) show eight individual 20 dBi gain pyramidal horns, made from double-clad FR-4 substrate material, attached at the edges of the horn separation slots in the Taconic RF-35 laminate substrate. Fig. 2(b) shows a closed up view of the centre of the antenna array, where the rotary switch and microstrip lines are located. Microwave absorber is included to minimize couplings between adjacent antennas. The side view at the antenna array is shown in Fig. 2(c).



(a)



(b)



(c)

Fig. 2. The assembled RF MEMS sectorised antenna array: (a) top view; (b) closed-up view at the centre and (c) side view.

III. MEASUREMENTS

Since there was no impedance matching for the SP8T RF MEMS rotary switch [35], coupled with 1 to 2 mm length bond wire interconnects, it should be of no surprise that the performance of this first ever experimental proof-of-concept prototype demonstrator would be far from optimal. Measurements of the overall input return loss for the complete antenna array, between 6 and 14 GHz and when the switch is making contact in all eight positions, are shown in Fig. 3. It can be seen that best performance is achieved at approximately 7 and 13 GHz.

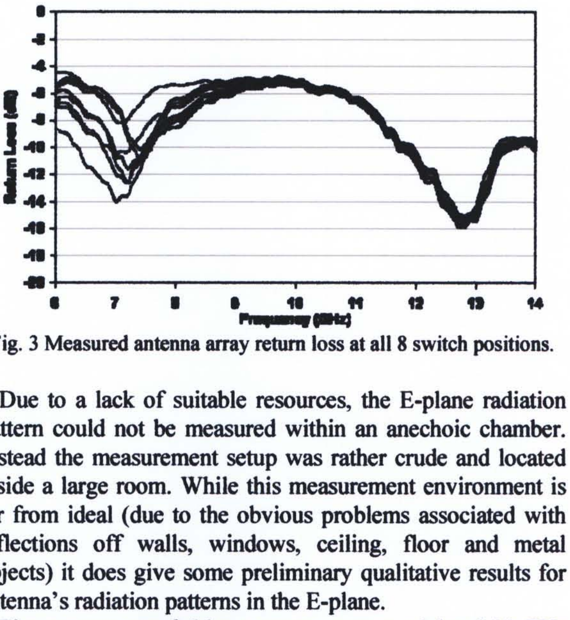
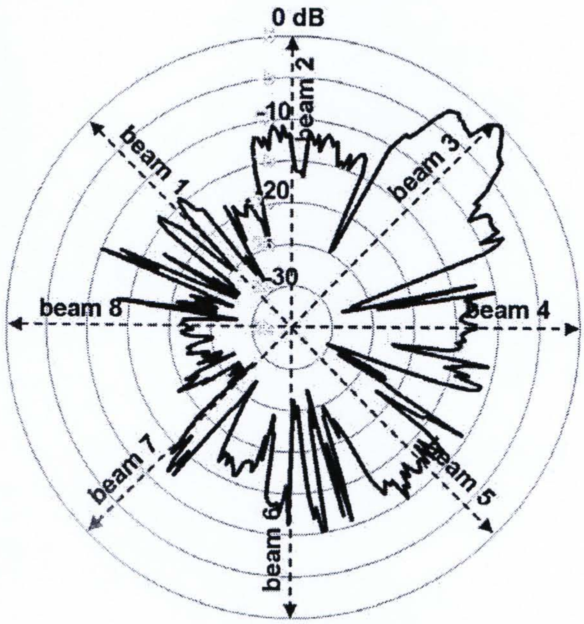


Fig. 3 Measured antenna array return loss at all 8 switch positions.

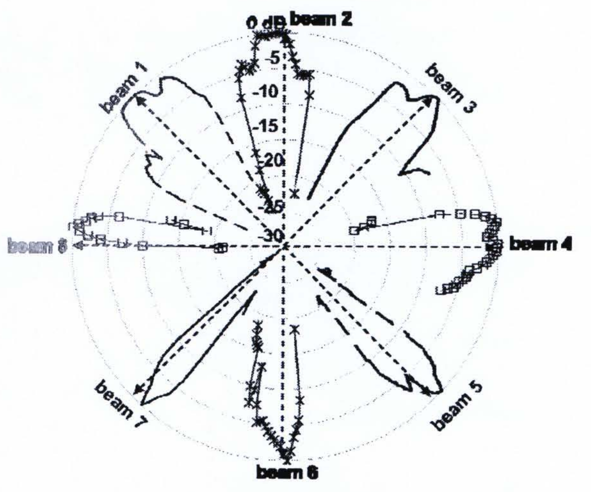
Due to a lack of suitable resources, the E-plane radiation pattern could not be measured within an anechoic chamber. Instead the measurement setup was rather crude and located inside a large room. While this measurement environment is far from ideal (due to the obvious problems associated with reflections off walls, windows, ceiling, floor and metal objects) it does give some preliminary qualitative results for antenna's radiation patterns in the E-plane.

The antenna was fed by a square-wave-modulated 10 GHz signal source, protected by an output isolator. A measurement setup to detect the received power (consisting of a reference pyramidal horn, a Schottky diode square law detector and a high gain IF amplifier) was then rotated around the sectorised horn antenna array in steps of either 1° or 2°.

With the SP8T RF MEMS rotary switch set to output position #3, the E-plane radiation pattern for the assembled sectorised horn antenna array was measured within the non-ideal environment. The preliminary results are shown in Fig. 4(a). In addition, Fig. 4(b) shows the results for the individual main beams when the switch is set to all eight positions.



(a)



(b)

Fig. 4 Measured radiation patterns for the sectorised horn antenna array (normalized to beam centres): (a) at switch/beam position #3 and (b) superimposed main beams for all eight switch positions

IV. Conclusions

A sectorised horn antenna array, employing a single-pole multiple-throw RF MEMS rotary switch, has been demonstrated for the first time. Even though the design of this first ever experimental proof-of-concept prototype demonstrator is not optimal and the test environment was far from ideal, preliminary measurements confirm the principle of operation for this novel antenna array. It is believe that with further work (e.g. optimization of the switch, individual radiating antenna elements and array assembly) a higher performance can be achieved.

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References

[1] S. Lucyszyn (Editor), "Advanced RF MEMS", Cambridge University Press, Cambridge, Sep. 2010

[2] J.-C. Chiao, Y. Fu, I. M. Chio, M. DeLisio and L.-Y. Lin, "MEMS reconfigurable Vee antenna", *IEEE MTT-S International Microwave Symposium Digest*, Anaheim, CA, pp. 1515-1518, 1999

[3] J.-C. Chiao, Y. Fu, D. Choudhury and L.-Y. Lin, "MEMS millimeterwave components", *IEEE MTT-S International Microwave Symposium Digest*, Anaheim, CA, pp. 463-466, 1999

[4] S. Lee, J.-M. Kim, J.-M. Kim, Y.-K, Kim, C. Cheon, and Y. Kwon, "V-band single-platform beam steering transmitters using micromachining technology", *IEEE MTT-S International Microwave Symposium Digest*, San Francisco, CA, pp.148-15, 2006

[5] C.-W. Baek, S. Song, C. Cheon, Y.-K. Kim and Y. Kwon, "2-D mechanical beam steering antenna fabricated using MEMS technology" *IEEE MTT-S International Microwave Symposium Digest*, San Francisco, CA, pp.211-214, 2001

[6] C.-W. Baek, S. Song, J.-H. Park, S. Lee, J.-M. Kim, W. Choi, C. Cheon, Y.-K. Kim and Y. Kwon, "A V-band micromachined 2-D beam-steering antenna driven by magnetic force with polymer-based hinges", *IEEE Transactions on Microwave Theory and Techniques*, vol. 51, no. 1, pp. 325-331, Jan. 2003

[7] C. G. Christodoulou, "RF-MEMS and its applications to microwave systems, antennas and wireless communications", *Proceedings of the SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference*, Foz do Iguaçu, Brazil, pp. 525- 531, 2003

[8] K. Topalli, O. A. Civi, S. Demir, S. Koc and T. Akin, "Dual-frequency reconfigurable slot dipole array with a CPW-based

feed network using RF MEMS technology for X- and Ka-band applications", *IEEE Antennas and Propagation Society International Symposium*, Honolulu, HI, pp. 825-828, 2007

[9] G. Liu, C. L. Law, M. J. Rajanik and H. Yang, "A switchable MEMS antenna for 38/60 GHz millimeter wave communications", *International Conference on Microwave and Millimeter Wave Technology Proceedings*, Beijing, China, pp. 86- 89, 2004

[10] C. W. Jung, M.-J. Lee, G. P. Li and F. De Flaviis, "Reconfigurable scan-beam single-arm spiral antenna integrated with RF-MEMS switches", *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 2, pp. 455- 463, Feb. 2006

[11] M. Maddela, R. Ramadoss and R. Lempkowski, "PCB MEMS-Based tunable coplanar patch antenna", *IEEE International Symposium on Industrial Electronics*, Vigo, Spain, pp. 3255-3260, 2007

[12] A. Sundaram, M. Maddela, R. Ramadoss and L. M. Feldner, "MEMS-based electronically steerable antenna array fabricated using PCB technology", *Journal of Microelectromechanical Systems*, vol. 17, no. 2, pp. 356-362, Apr. 2008

[13] W. Gautier, B. Schoenlinner, V. Ziegler, U. Prechtel and W. Menzel, "LTCC patch array for RF-MEMS based phased array antenna at 35GHz" *38th European Microwave Conference*, Amsterdam, pp. 151-154, 2008

[14] C.-C. Cheng, B. Lakshminarayanan and A. Abbaspour-Tamijani, "A programmable lens-array antenna with monolithically integrated MEMS switches", *IEEE Transactions on Microwave Theory and Techniques*, vol. 57, no. 8, pp. 1874-1884, Aug. 2009

[15] W. Gautier, A. Stehle, C. Siegel, B. Schoenlinner, V. Ziegler, U. Prechtel and W. Menzel, "Hybrid integrated RF-MEMS phased array antenna at 10GHz" *38th European Microwave Conference*, Amsterdam, pp. 139-142, 2008

[16] W. Gautier, V. Ziegler, A. Stehle, B. Schoenlinner, U. Prechtel and W. Menzel, "RF-MEMS phased array antenna on low-loss LTCC substrate for ka-band data link", *European Microwave Conference*, Rome, pp. 914-917, 2009

[17] C. Zhang, M. Kuhn, M. Mahfouz and A. E. Fathy, "Planar antipodal Vivaldi antenna array configuration for low cross-polarization and reduced mutual coupling performance", *IEEE Antennas and Propagation Society International Symposium*, Honolulu, HI, pp. 725-728, 2007

[18] L. Ying and C. Ai-Xin, "Design and application of Vivaldi antenna array", *International Symposium on Antennas, Propagation and EM Theory*, Kunming, China, pp. 267-270, 2008

[19] L. R. Lewis, M. Fassett and J. Hunt, "A broadband stripline array element", *Antennas and Propagation Society International Symposium*, pp. 335- 337, 1974

[20] P. J. Gibson, "The Vivaldi aerial", *9th European Microwave Conference*, pp. 101-105, 1979

[21] A. Z. Hood, T. Karacolak and E. Topsakal, "A small antipodal Vivaldi antenna for ultrawide-band applications", *IEEE Antennas and Wireless Propagation Letters*, vol.7, pp. 656-660, Mar. 2008.

[22] D. Schaubert, E. Kollberg, T. Korzeniowski, T. Thungren, J. Johansson and K. Yngvesson, "Endfire tapered slot antennas on dielectric substrates", *IEEE Transactions on Antennas and Propagation*, vol. 33, no. 12, pp. 1392- 1400, Dec. 1985

[23] R. Janaswamy and D. Schaubert, "Analysis of the tapered slot antenna", *IEEE Transactions on Antennas and Propagation*, vol. 35, no. 9, pp. 1058-1065, Sep. 1987

[24] K. S. Yngvesson, T. L. Korzeniowski, Y.-S. Kim, E. L. Kollberg and J. F. Johansson, "The tapered slot antenna – a new integrated element for millimeter-wave applications", *IEEE Transactions on Microwave Theory and Techniques*, vol. 37, no. 2, pp. 365-374, Feb. 1989

[25] J. Shin and D. H. Schaubert, "A parameter study of stripline-fed Vivaldi notch-antenna arrays", *IEEE Transactions on Antennas and Propagation*, vol. 47, no. 5, pp. 879-886, May 1999

[26] T. G. Lim, H. N. Ang, I. D. Robertson, and B. L. Weiss, "Tapered slot antenna using photonic bandgap structure to reduce substrate effects", *Electronics Letters*, vol. 41, no. 7, pp. 393-394, Mar. 2005

[27] P. Li, J. Liang and X. Chen, "UWB tapered-slot-fed antenna", *The Institution of Engineering and Technology Seminar on Ultra Wideband Systems, Technologies and Applications*, London, pp. 235-238, 2006

[28] P. Cerny, J. Nevrly and M. Mazanek, "Optimization of tapered slot Vivaldi antenna for UWB application", *19th International Conference on Applied Electromagnetics and Communications*, Dubrovnik, pp. 1-4, 2007

[29] A. O. Boryssenko, D. H. Schaubert and C. Craeye, "A wave-based model for mutual coupling and truncation in finite tapered-slot phased arrays", *IEEE Antennas and Propagation Society International Symposium*, Columbus, OH, pp. 11-14, 2003

[30] M. Wang, W. Wu and C. Miao, "Mutual coupling effect on bandwidth of Vivaldi arrays", *IEEE Antennas and Propagation Society International Symposium*, Charleston, SC, pp.1-4, 2009

[31] A. O. Boryssenko and D. H. Schaubert, "Physical aspects of mutual coupling in finite broadband tapered slot (Vivaldi) arrays", *International Conference on Antenna Theory and Techniques*, Kyiv, Ukraine, pp. 74-79, 2005

[32] K. Van Caekenberghe and T. Vaha-Heikkila, "An analog RF MEMS slotline true-time-delay phase shifter", *IEEE Transactions on Microwave Theory and Techniques*, Scottsdale, AZ, pp. 2151-2159, 2008

[33] S. Capdevila, M. Jofre, J. Rodriguez, M. Guardiola, A. Papio, F. De Flaviis and L. Jofre, "UWB MST MEMS-based near-field imaging system", *IEEE 2008 Antennas and Propagation Society International Symposium*, San Diego, CA, pp. 1-4, 2008

[34] J. C. Rock, T. Hudson, B. Wolfson, D. Lawrence, B. Pillans, A. R. Brown and L. Coryell, "A MEMS-based, Ka-band, 16-element sub-array", *IEEE Aerospace conference*, Big Sky, MT, pp. 1-11, 2009

[35] S. Pranonsatit, A. S. Holmes, I. D. Robertson and S. Lucyszyn, "Single-pole eight-throw RF MEMS rotary switch", *Journal of Microelectromechanical Systems*, vol. 15, no. 6, pp. 1735-44, Dec. 2006

[36] S. Pranonsatit, A. S. Holmes and S. Lucyszyn, "Microwave modelling of RF MEMS rotary switches", *IET Microwaves, Antennas and Propagation*, 2011

[37] T. Thungren, E. L. Kollberg and K. S. Yngvesson, "Vivaldi antennas for single beam integrated receivers," in *European Microwave Conference*, Helsinki, Finland, pp. 361-366, 1982

[38] R. O. Lee and R.N. Simons, "Effect of curvature on tapered slot antennas", *Antennas and Propagation Society International Symposium*, Baltimore, MD, pp.188-191, 1996