International Journal of Electronics
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tetn20

Dual-mode quadruple ridge waveguide feed for broadband satellite communications

A.J. Sangster [a] & J. Grant [b]

[a] Department of Electronic and Computer Engineering, School of Engineering and Physical Sciences, Heriot-Watt University, Riccarton, Edinburgh, EH14 4AS

[b] Scotsat Ltd., 21 Huntley Gardens, Glasgow, G12 9AU, UK

Version of record first published: 12 Sep 2012.

To cite this article: A.J. Sangster & J. Grant (2012): Dual-mode quadruple ridge waveguide feed for broadband satellite communications, International Journal of Electronics, DOI:10.1080/00207217.2012.720954

To link to this article: http://dx.doi.org/10.1080/00207217.2012.720954

International Journal of Electronics
2012, 1–10, iFirst

Dual-mode quadruple ridge waveguide feed for broadband satellite communications

A.J. Sangster[a]* and J. Grant[b]

[a]*Department of Electronic and Computer Engineering, School of Engineering and Physical Sciences, Heriot-Watt University, Riccarton, Edinburgh, EH14 4AS;* [b]*Scotsat Ltd., 21 Huntley Gardens, Glasgow, G12 9AU, UK*

(*Received 7 March 2012; final version received 27 July 2012*)

A novel and compact dual-channel multimode waveguide system is described, which permits two distinct frequency channels, such as C-band and Ku-band, to be propagated simultaneously. The system is also dual-moded at both the lower and the upper frequencies, thus enabling polarisation switching between orthogonal linear signals or between left and right hand circularly polarised transmissions. The development is primarily motivated by the desire to provide extended range and global coverage, for a maritime satellite communications system, employing a single antenna platform.

Keywords: communications; electromagnetism; multimode, satellite; waveguide

1. Introduction

In this article, an electromagnetic waveguide is described, which displays the ability to provide low loss propagation over a frequency range extending to four octaves, while at the same time it is capable of supporting orthogonal modes to accommodate linear and circular polarisation. The aim of the development has been to achieve this versatility with a relatively compact uncomplicated design in a structure with symmetrical cross-section.

Guiding structures that exhibit the potential to meet the above requirement are actually quite limited in number. Examples are square or cylindrical corrugated waveguide (Rao 1990), quadruple-ridge waveguide (Chen 1974; Chen et al. 1974; Rong and Zaki 2000; Mclean 2005), and dual channel waveguide comprising a coaxial line with a cylindrical waveguide embedded within the inner conductor (Adams 1988; Ergene 2001).

The bandwidth of a corrugated feed waveguide is essentially governed by the cut-off frequency of the dominant HE_{11} hybrid mode and the frequencies at which higher order modes can co-exist. These higher order modes, if they are permitted to form, cause radiation pattern degradation and cross-polar lobes when the guide is flared into a corrugated horn radiator. While the equivalent smooth walled cylindrical waveguide feeding into a conical horn exhibits a bandwidth of no more than 30% for single mode operation, the corrugated counterpart can be much wider by taking advantage of its

*Corresponding author. Email: a.j.sangster@hw.ac.uk

ISSN 0020–7217 print/ISSN 1362–3060 online

http://dx.doi.org/10.1080/00207217.2012.720954
http://www.tandfonline.com

filter characteristics. Low loss transmission bands occur at frequencies which are integer multiples of the main pass-band. Evidently, these can be used to secure operation at C-band (main pass-band) and at Ku-band in an upper pass-band, which is approximately three times higher in frequency. However, as a front fed feed for a parabolic reflector based communications antenna, this structure has distinct limitations, because maintaining close to optimum reflector illumination over a three octaves frequency range, is challenging the physics of the fixed aperture feed antenna.

Ridged waveguide horn antennas are used extensively in antenna test systems because of their very wide bandwidth capability – 1–18 GHz being typical. Consequently, a quadruple ridge waveguide design exhibiting an operational bandwidth of 3–13 GHz, for a C/Ku-band satellite communications application, is clearly feasible. The major dimensions of such a waveguide are not too dissimilar to those of the corrugated structure discussed above. The height of the four ridges in the input cylindrical waveguide has to be at least 80% of the waveguide radius to ensure that higher order modes are suppressed over a 3:1 frequency range. Consequently, the resultant inter-ridge gap, which ensures that modal problems are insignificant, is relatively small and this raises difficult technical issues for the design of low band (coaxial line) and high band (cylindrical waveguide) transitions. In addition, as a feed for a communications antenna, this structure is also problematic in a manner not too dissimilar to that of the corrugated horn. To form an antenna the quadruple ridge guide is usually terminated in a tapered ridge horn. Again, the fixed horn aperture, as with the corrugated horn, displays a troublesome degree of beam-width sensitivity to changing frequency, for an application which seeks operation over a three octaves bandwidth. While the tapered ridge horn is less sensitive to radiation pattern distortion due to moding than a corrugated horn, the control of higher order modes can still be an issue (Sangster and Grant 2009).

Dual channel coaxial waveguide is essentially two electromagnetic wave guiding structures embedded within each other, which are usually independently excited from totally separate input systems (Lui et al. 1977). The low-frequency mode is carried by a coaxial waveguide which, in an antenna feed role, flares into a conical horn. The dual channel capability is achieved by making the inner of the coaxial waveguide hollow, so that an embedded cylindrical waveguide propagating structure is formed which carries the upper frequency mode. In antenna applications, the radiation mechanism for this mode is usually a tapered dielectric rod antenna located in the distal end. The bandwidth requirements of a system designed to operate over the C/Ku satellite bands are comfortably met, since the coaxial guide and hollow inner conductor essentially comprise two independent propagation systems – one tuned to C-band the other tuned to Ku-band. However, the TEM mode in coaxial waveguide is not a naturally radiating mode. Open-ended coaxial line behaves essentially as an open-circuit as one would expect. Mode conversion to the higher order TE_{11} mode of coaxial line (at C-band), by means of a rather complex space consuming transducer is required to procure efficient radiation in feed applications. This mode transducer requirement is a distinct disadvantage for installation of a coaxial waveguide based feed configuration, on a space limited antenna platform for maritime satellite communications.

The new approach outlined in this article achieves a compact dual-channel waveguide propagating structure by taking advantage of the intrinsic bandwidth of the quadruple ridge waveguide, but differs from previous developments by embedding a pair of orthogonally orientated rectangular waveguides within hollow ridges.

2. Quad-ridge waveguide with channelised ridges

2.1. *Quad-ridge waveguide*

Electromagnetic modelling studies, which have been carried out on dual-ridge, quad-ridge and octo-ridge cylindrical waveguides (Sangster and Grant 2009), have exposed serious bandwidth limitations as alluded to above. But, rather interestingly, in addition to demonstrating these bandwidth deficiencies, the simulations have revealed that a range of low order modes can occur on quad-ridge and octo-ridge structures, whose fields exist mainly in the inter-ridge spaces rather than in the ridge gaps.

The mode depicted in Figure 1 is a clear example generated using a commercial finite element electromagnetic solver (COMSOL). We have termed modes of this nature, channel modes. The electric field pattern of the mode depicted is strongly radial in the inter-fin spaces with axial (normal to the page) field components in the central region. As can be seen, this channel mode is a quasi-TM_{11} mode of the cylindrical waveguide. It exists for quite deep ridges.

2.2. *Channelised quad-ridge waveguide*

The above observation was instrumental in the development of the idea of forming a ridge waveguide structure, which enables the Ku-band to exist on quasi-TE_{11} ridge modes (Sangster and Grant 2009), while supporting C-band independently in 'isolated' channel modes. The concept is illustrated in Figure 2, which shows simulated fields for a quad-ridge structure with hollowed out ridges. Figure 2 depicts the quasi-TE_{11} ridge mode between the vertically orientated pair of hollowed out ridges. A wide range of ridge heights

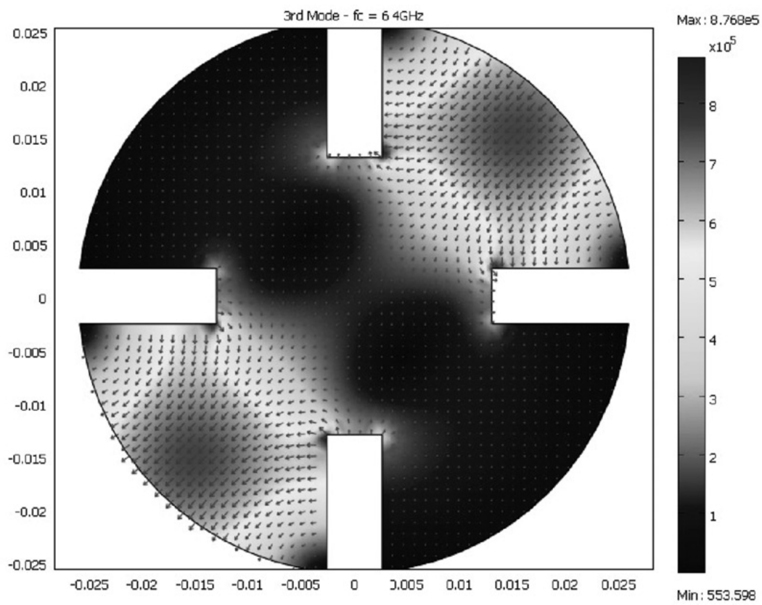


Figure 1. E-field distribution of quad-ridge waveguide channel mode (dark area = low intensity: light areas = high intensity).

have been examined to establish the channelling principle. It is well known that the quasi-TE_{11} mode morphs into the TEM mode as the ridge height to guide radius ratio tends towards unity.

The electric field is mainly in the y-direction between the excited ridge pair at the top and bottom of the figure. These are hollow. The orthogonal ridge pair is made solid to best illustrate the basic field pattern. It is pertinent to note here, that there is a distinct absence of fields within the hollow channel space of the supporting ridges. Fields in this region (i.e. within the ridge), if they exist, are at least 30 dB down on the desired field in the ridge gap.

In Figure 3, the horizontal ridge pair has been excited by a TE_{10} rectangular waveguide mode, which propagates efficiently at C-band despite the ridge gap. Here the E-field is again mainly y-directed between the upper and lower conducting walls of the low height waveguide.

2.3. *Dual-mode ridge waveguide*

The above observations were instrumental in the development of a novel ridge waveguide structure (Sangster and Grant 2010), which enables Ku-band to exist on quasi-TE_{11} ridge modes, while supporting C-band independently in channel modes (see Figure 4).

At its radiating end (on the left of Figure. 4), the proposed feed houses a tapered cylindrical dielectric rod (black) to control the high band radiation pattern (Rong and Zaki 2000), while the cylindrical outer conducting wall of the hollow-ridge feed is suitably flared or stepped (boxed structure) to form a conical horn to control the low band pattern. The right hand portion of the drawing (Figure 4) illustrates the proposed input/output

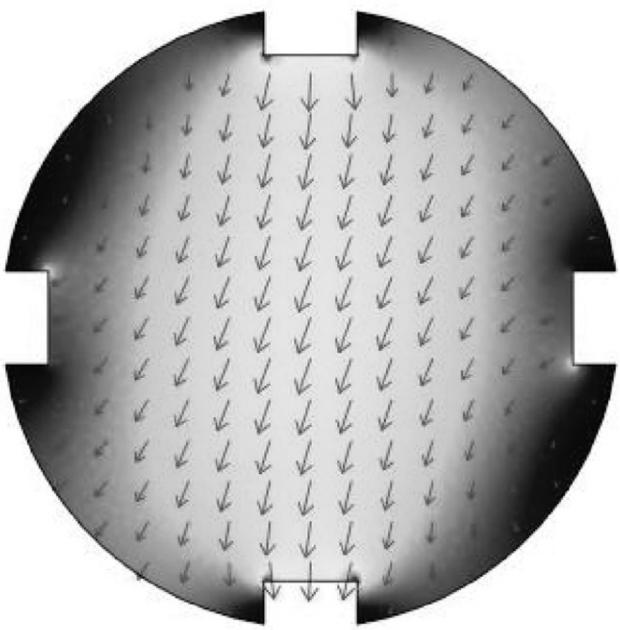


Figure 2. Quad-ridge structure showing quasi-TE_{11} (TEM) mode supported by ridges.

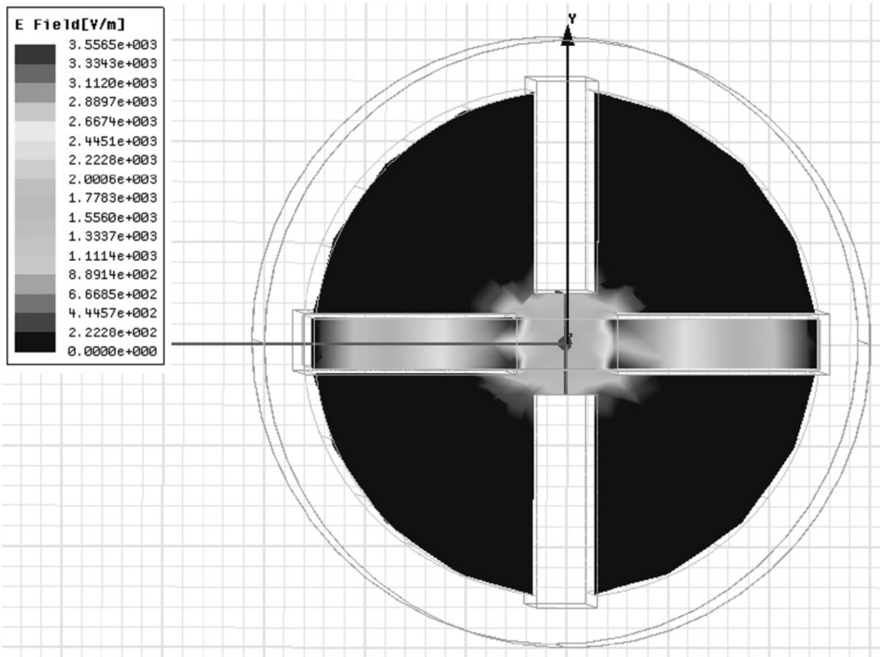
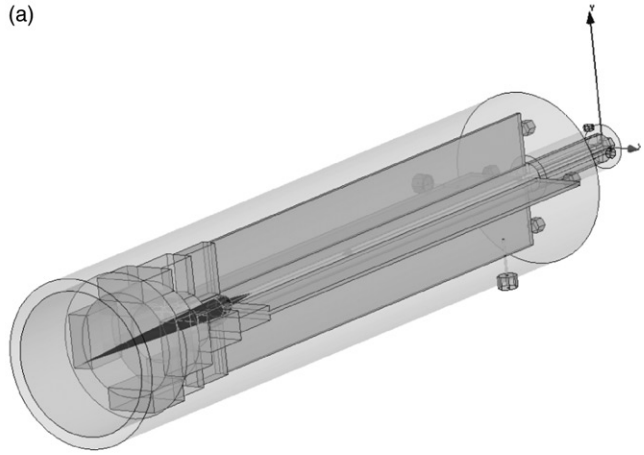


Figure 3. Channelised quad-ridge structure showing TE_{10} mode in the channels (black = zero field: light gray = low field: dark gray = high field).

electromagnetic wave launching schemes for both the low and high band waveguide structures, and possible tuning arrangements to optimise impedance matching between the guides and the coaxial feed lines.

The ridge height as a ratio of the radius R of the cylindrical housing (h/R) and width ratio (w/R) (see Figure 4a) are chosen to maximise bandwidth at Ku-band with ridges that are not too thin for channelisation. For C/Ku band operation this results in a structure with the following dimensions: $h = 2.5$ mm, $w = 2.5$ mm, $R = 8.33$ mm, $a = 70$ mm, $b = 1.5$ mm, where a is the channel guide width and b is its height. The modelling studies suggest that the quasi-TE_{11} ridge mode at Ku-band propagates with very low loss and with negligible energy, as Figure 2 shows, leaking into the hollow ridge space. Actually, if one or two filamentary conducting wires – an option which is being examined – are located at the top of the channelled ridge and are organised to run axially (z-direction) along the length of the ridge, field leakage into the channels of the guiding ridges is essentially eliminated (more than 50 dB down). Such wires have negligible effect on the TE_{10} channel mode whose field is transversely directed (x or y-direction). The simulations also indicate that at the Ku-band a bandwidth of about 40% centred on 12 GHz is readily achievable, while at C-band, using rectangular waveguide estimates, a bandwidth of about 55% centred on 4 GHz is available.

Figure 2 demonstrates that a relatively undistorted quasi-TE_{11}/TEM mode is secured in the ridge gap, despite the hollow ridges. However, when the orthogonal pair of ridges is also channelised, field leakage at Ku-band sets up an unwanted TE_{30} mode in the transversely located channels (Figure 5a). At C-band this mode is fully cut-off. While the presence of this mode is unfortunate, it turns out that within the specified frequency range, it is the only



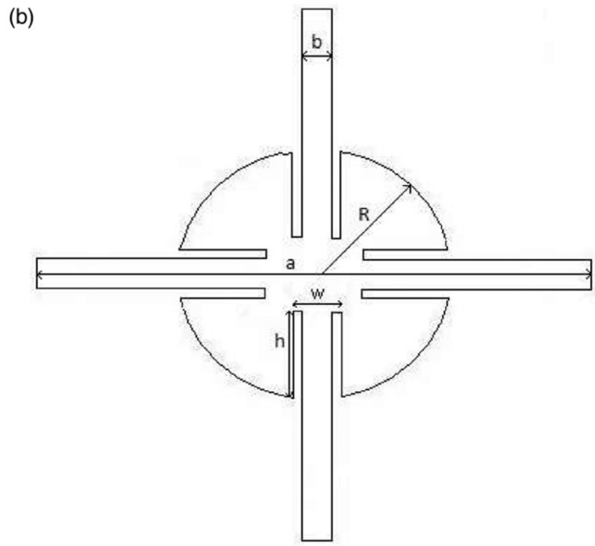


Figure 4. Drawings of proposed feed design (a) three dimensional (b) cross section.

undesirable mode that can be induced in the structure. Also, it has a well defined field pattern, which means that it is easy to suppress with judicially located absorbing strips, as shown in Figure 5(b). The simulation shows high absorption for a 1.5 mm thick lossy strip ($\rho = 1.0\,\Omega$m) located 10 mm from the sidewall. In this position, the suppression strips have negligible influence on the rate of attenuation of the TE_{10} mode at C-band.

2.4. *Proposed feed*

A prototype of the proposed dual-channel multi-mode feed horn has been fabricated. It is intended to be used with a parabolic reflector antenna in range measurements and satellite

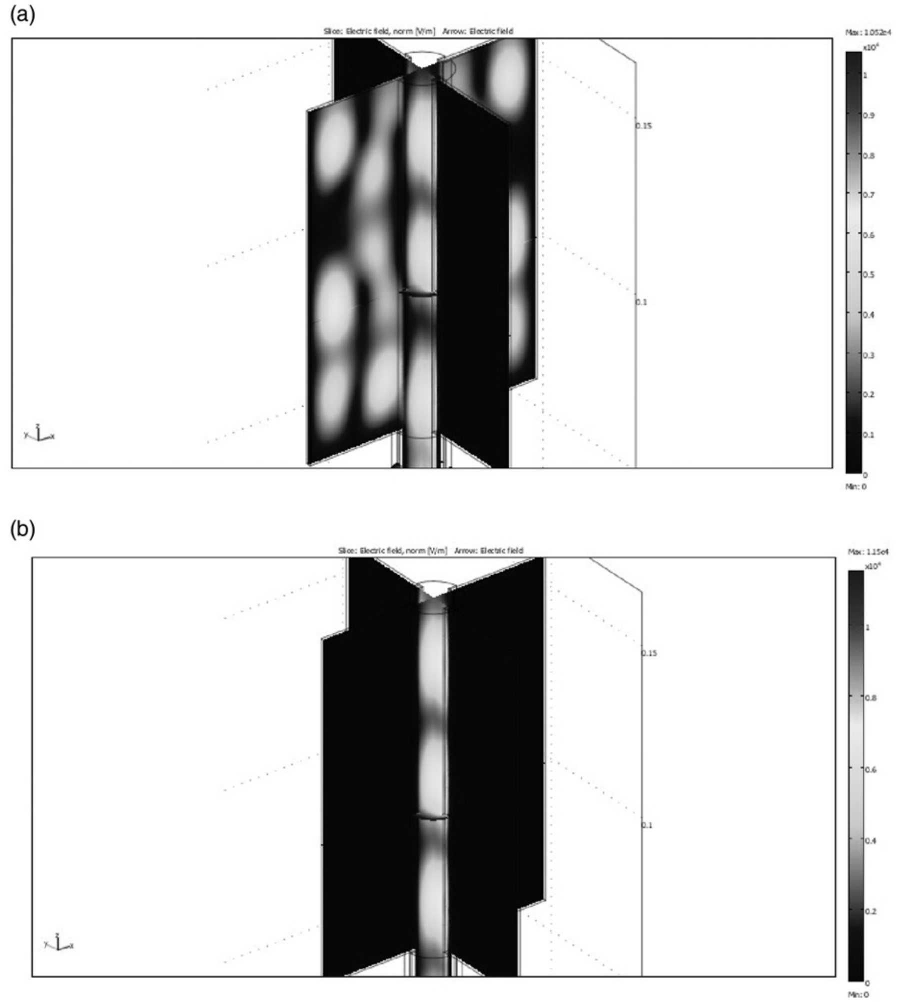


Figure 5. Quasi-TE_{11} ridge mode showing unwanted TE30 mode in the low frequency channel waveguide: (a) no suppression, (b) with suppression.

acquisition tests at C-band and Ku-band frequency ranges. It comprises a quad-ridge-loaded cylindrical waveguide, a section of which is shown in Figure 6. The feed is formed by carefully stacking together 20 of these 1 cm thick units. The guide dimensions are provided in Section *C*. The split-ridge within the cylindrical aperture supports the high frequency band by means of independent orthogonal quasi-TE_{11} ridge modes. The orthogonality of the modes permits polarisation agility or switching.

The low frequency band is directed into the ridge channels which, as the photograph clearly shows, form a pair of mutually orthogonal low height rectangular waveguides. The hollow ridges thus support a pair of independent orthogonally orientated TE_{10} modes, which permit polarisation switching and circular polarisation at C-band.

High isolation, as suggested in the preceding section, between Ku-band and C-band can be encouraged by introducing axial conducting strips, supported by a low loss,

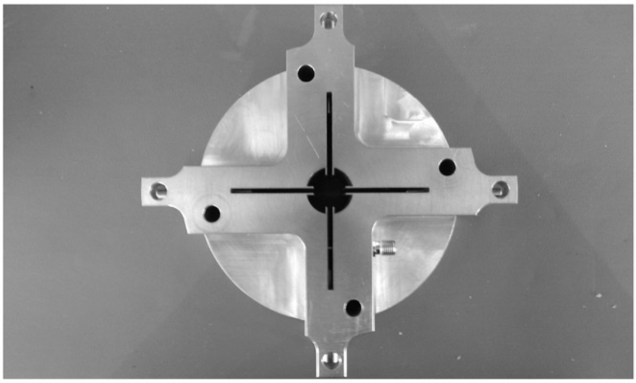


Figure 6. Spark-eroded and machine disk element of a prototype channellised waveguide feed.

low permittivity, dielectric foam insert, partially filling the hollow ridges. This ensures that the ridges appear 'solid' to the high band fields, while they have negligible effect on the TE_{10} mode field patterns. However, laboratory testing indicates that acceptable isolation levels are probably available without wire inserts.

The low height channel waveguide will be subject to power restriction as a possible consequence of electric field breakdown across the narrow dimension. To assess this restriction, calculations have been performed on an air filled rectangular waveguide with the wide dimension $a = 70$ mm and the narrow dimension $b = 1.5$ mm. The calculation has been performed for a mid C-band frequency (5 GHz), and it is assumed that air breaks down at an electric field strength of 2.7 kV/mm. Integration of power density for the TE_{10} mode over the cross-section of the waveguide yields the following equation for power:

$$P_{\max} = \frac{1}{4}|E|^2 \frac{\beta_g}{\omega\mu_0} ab \text{ Watts}$$

For the given waveguide at 5 GHz, $\beta_g = 0.087$ rad/mm, while $\omega\mu_0 = 39.48$ rad/Ωmm. Consequently,

$$P_{\max} = \frac{1}{4} \times 2700^2 \times \frac{0.087}{39.48} \times 70 \times 1.5 = 421.7 \text{ kW}$$

In practice edge effects and other structural influences will lower this figure. Nevertheless, it is clear that power handling will not present a problem for the proposed feed in a low power satellite communications application.

2.5. *Preliminary system tests*

As shown in Figure 7, the prototype feed was installed on a mobile 1.8 m diameter satellite communications parabolic reflector, and pointed at known northern hemisphere satellites, to test the system in a satellite acquisition role. The feed is coupled through a commercial amplification and filtering stage to a spectrum analyser linked to a laptop computer. The combination provided effective visual evidence of the acquisition of a signal and demonstrable locking at Ku-band and at C-band, thus confirming that this new feed

Figure 7. Satellite acquisition test showing lock at Ku-band.

design is potentially capable of meeting developing maritime dual-channel satellite communications roles.

3. Conclusions

A new dual-band feed waveguide structure is described comprising a quad-ridge waveguide structure with hollow ridges. It provides high isolation between widely separated communication channels propagating conventionally on the ridge structure (high band) and uniquely in the hollow ridges (low band) which form a pair of orthogonal low height rectangular waveguides. This compact package is intended to be employed in a ship-borne satellite communications role.

Preliminary testing of a prototype system, which will be discussed in detail in a follow-up article, indicates that the feed operates as designed. However, it is evident that considerable development continues to be needed in order to optimise bandwidth performance by avoiding moding, and to minimise insertion losses by reducing leakage and mismatch problems displayed by the prototype.

References

Adams, E.A. (1988), 'Dual Frequency Feed Satellite Antenna Horn', US Patent No. 4,785,306.

Chen, C.C. (1974), 'Quadruple Ridge-loaded Circular Waveguide Phased Arrays', *IEEE Transactions on Antennas and Propagation*, AP-22, 481–483.

Chen, C.C., Tsandoulos, G.N., and Willwerth, F.G. (1974), 'Modal Characteristics of Quadruple-ridge Circular and Square Waveguide', *IEEE Transactions on Antennas and Propagation*, AP-22, 801–804.

Ergene, A. (2001), 'Dual Band Multimode Coaxial Tracking Feed', US Patent No. 6,323,819 B1.

Lui, C.C-Y., and Fuller, J.A. (1977), 'Coaxial Waveguide Antenna', US Patent No. 4,041,499.

Mclean, J.S. (2005), 'Dual and Quad Ridged Horn Antenna', US Patent No. 7,161,550.

Rao, K.S. (1990), 'A Simple Dual-band Corrugated Horn with Low Cross Polarisation', *IEEE Transactions on Antennas and Propagation*, AP-38, 946–950.

Rong, Y., and Zaki, K.A. (2000), 'Characteristics of Generalised Rectangular and Circular Ridge Waveguides', *IEEE Transactions on Microwave Theory and Techniques*, MTT-48, 258–265.

Sangster, A.J., and Grant, J. (2009), 'Mode Degeneracy in Circular Cylindrical Ridge Waveguides', *Progress in Electromagnetics Research*, 9, 75–83.

Sangster, A.J., and Grant, J. (2010), 'Waveguide Apparatus', Patent Application No. UK1005360.1.