Towards Standardized Waveguide Sizes and Interfaces for Submillimeter Wavelengths

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***Abstract*—This paper describes an activity that has begun recently to develop an international standard for rectangular metallic waveguides and their interfaces for frequencies of 110 GHz and above. The IEEE's Microwave Theory and Techniques Society (MTT-S) is sponsoring the development of this standard. The MTT-S Standards Committee has set up the P1785 Working Group tasked with undertaking the work that is necessary to write this standard. This paper describes the work to date of this Working Group and the future activities that will be necessary to complete the standard.**

***Index terms*—Waveguides, rectangular waveguides, millimetre-wave, submillimeter-wave, waveguide flanges, waveguide interfaces**

I. INTRODUCTION

At the present time, no international document standards exist for defining sizes and interfaces for rectangular metallic waveguides used at submillimeter wavelengths (i.e. at frequencies above 325 GHz). Some proposals for sizes and interfaces have been published in recent years (e.g. [1-7]) but these have not yet been adopted by any of the international standards-making bodies (e.g. ISO, IEC, IEEE). This situation was recognized recently by the IEEE Standards Association, and this has led to a project being initiated to put in place an IEEE standard for both waveguide sizes (i.e. the aperture dimensions) and their associated interfaces (e.g. flanges) suitable for use at all frequencies above 110 GHz. Although standards already exist for waveguides in the 110 GHz to 325 GHz range (see, for example, [8, 9]), these waveguides will also be included in the new IEEE standard to allow their tolerances to be re-evaluated in the context of contemporary manufacturing capabilities.

The development of the new standard is being sponsored by the Standards Committee of the IEEE's Microwave Theory and Techniques Society (MTT-S). A working group has been set up (and assigned the project number P1785) that will write the standard and ensure that it is published in a timely manner. This working group held its first meeting during the International Microwave Symposium (IMS) in Atlanta, GA, USA, in June 2008. The working group has since met a further three times (i.e. approximately every six months), with the next meeting scheduled to take place during IMS in Anaheim, CA, USA, in May 2010 (www.ims2010.org). Membership of the P1785 Working Group is open to all persons with an interest in this area, and membership to the P1785 Working Group can be achieved by attending at least one, or more, of the working group meetings. The working group currently has 22 members.

It is envisaged that the standard will be published in two parts: one part dealing with waveguide dimensions and recommended frequency bands; the other part dealing with waveguide interfaces (including flanges). The working group is already making good progress with Part 1 of the standard and it is likely that a first draft will be available for public comment during 2011.

This paper gives a review of all the activities of the P1785 Working Group. The paper describes the progress of the working group to date – specifically, the work on defining frequency bands and waveguide aperture dimensions. This includes a review of the waveguide size scheme that has been provisionally chosen for inclusion in the IEEE standard. The paper also describes the planned working group activities for the future, including: the other remaining steps needed to complete Part 1 of the standard; and, information about waveguide interfaces to be included in the standard. More information about the standard, and the activities of the P1785 Working Group, can be found at: **http://grouper.ieee.org/groups/1785**.

II. PROGRESS TO DATE

Much of the first two meetings of the P1785 Working Group, in June and December 2008, were concerned with defining the general scope of the standard and the level of detail for the information to be included in the standard. It was also agreed during these early discussions that metric units[1] (i.e. millimeter and micron) will be used in the standard, rather than the Imperial units (i.e. inch and mil) that had been used in the existing MIL standard [8]. Similarly, although no official standard for frequency bands and waveguide dimensions currently exists for frequencies above 325 GHz, it was recognised that a significant amount of scientific work is already taking place at these higher frequencies. Much of this work has used the proposed

[1] Following the International System of units (i.e. **S**ystème **I**nternational d'unités, abbreviated to **SI**).

frequency bands given in [3] – see, for example, [10] and [11]. These waveguide bands use an extension of the WR naming convention given in the MIL standard [8], leading to waveguide names such as WR-2.8, WR-2.2, etc. However, the dimensions of these waveguide bands are defined in terms of Imperial units[2] and so do not meet the agreed requirement that the IEEE standard will use dimensions defined in terms of metric units.

At the third P1785 Working Group meeting (in Boston, MA, USA, in June 2009), a great deal of attention was given to the subject of defining the waveguide frequency bands and aperture sizes. This led to the setting up of a dedicated sub-group, within the P1785 Working Group, tasked with recommending to the main P1785 Working Group potential schemes for defining waveguide frequency bands and aperture sizes. This sub-group[3], with membership from the USA and Europe, communicated regularly using email and teleconferencing. Over a period of six months or so, the sub-group developed a series of potential waveguide schemes that fitted, to a greater or lesser degree, some generally agreed design criteria. However, it also became clear that no unique waveguide scheme existed that perfectly met all the design criteria. The ten design criteria that were established during this process are described below.

A. Frequency bands

The frequency bands (i.e. the suggested lower and upper frequencies of each waveguide band) should:

1. Be memorable (i.e. use whole numbers);
2. Form two contiguous interleaved series (i.e. should not contain gaps or overlaps in the frequencies covered by each series);
3. Be easily extendable from lower frequencies to higher frequencies (i.e. mapping from one decade to the next);
4. Agree with the existing values for WR-10 to WR-03, as given in the MIL standard [8].

B. Waveguide dimensions

It was soon agreed that a ratio of 2:1 would be used to describe the relationship between the waveguide aperture width and height (i.e. the ratio of the broad- to narrow-wall dimensions). Therefore, it was only necessary to define the waveguide broad-wall dimension (called the 'width', by convention). The waveguide widths should:

5. Where appropriate, be effectively identical (within stated tolerances) to sizes WR-10 to WR-03, as given in the MIL standard [8]);
6. Where appropriate, be very similar to sizes WR-2.8 to WR-1.0, as given in [3];
7. Avoid fractional micron values (i.e. *x.y* microns).

C. Related quantities

In addition to the above, the waveguide scheme should provide, for all bands:

8. Relatively uniform fractional bandwidths;
9. Approximately constant *k*-factors[4] (where $k_1 \approx 1.25$ and $k_2 \approx 1.90$);
10. Similar ratios of cut-off frequencies (or, equivalently, waveguide widths) for adjacent bands.

The subgroup developed a spreadsheet to assist in the development and evaluation of candidate waveguide schemes. The spreadsheet included plots of size deviations from current standards, worst-case reflection coefficients due to these size deviations, cutoff-frequency ratios, fractional bandwidths, and *k*-factors. This spreadsheet will soon be made available at: **http://grouper.ieee.org/groups/1785**. The spreadsheet and design criteria discussed above were used to establish a short-list of three candidate waveguide schemes[5] that were presented subsequently to the P1785 Working Group for discussion, followed by a vote.

The first scheme was derived from [3]. It retained the familiar WR names and recommended operating bands currently being used, but used metric sizing. This scheme resulted in excellent compatibility with existing practice and retained familiar nomenclature and operating bands while providing a metric framework for dimensions. The disadvantages were seen to be an irregularity in the progression of the scheme, fractional numbers in the nomenclature and significant variations in the mismatch and *k*-factor spread.

The second scheme was developed within the subgroup itself [12], and used the names WM *n*, where *n* was an integer or half integer denoting the waveguide size. This resulted in names of the form WM 0, WM 0.5, WM 1, WM 1.5, etc, keeping names short and making it easy to identify neighbouring bands. Sizes for WM 0 to WM 2.5 were chosen from a table to correspond closely to existing standards, but above WM 2.5, the waveguide width, *a*, is determined by rounding $10^{(-2n/11)} \times 2540$ µm to three significant digits. This formula-based approach ensured a uniform and unlimited geometric progression of center frequencies with exceptionally uniform operating bandwidths to simplify the development of certain instrumentation and even allowed for the natural definition of quarter-band sizes when necessary, while keeping deviations from established bands below the measureable limits of today's instrumentation and standards. However, the scheme did break from the convention of using the waveguide sizes themselves as names, changing the current nomenclature style by having numbers increasing with decreasing waveguide size, and adjusted recommended operating frequency bands somewhat from existing practice.

[2] The number 2.8 in the name WR-2.8 refers to the defined broad-wall dimension of the waveguide, i.e. (2.8 ×10) mil = 28 mil.

[3] The members of the subgroup were Jeffrey Hesler, Anthony Kerr, Roger Pollard, Nick Ridler and Dylan Williams.

[4] These *k*-factors are the multipliers used to establish the suggested minimum frequency, f_{min}, and maximum frequency, f_{max}, from the cutoff-frequency, f_c, for each waveguide band: $f_{min} = k_1 \times f_0$; $f_{max} = k_2 \times f_0$.

[5] Two of these schemes were derived from [3] and [6], along with a third scheme proposed in [12].

The provisional scheme eventually selected, following a discussion and vote by the P1785 Working Group, is shown in Table 1, where *a* and *b* refer to the width and height dimensions of the waveguides, respectively.

TABLE I
PROPOSED FREQUENCY BANDS AND WAVEGUIDE DIMENSIONS FOR THE IEEE STANDARD

Name	*a* (μm)	*b* (μm)	f_c (GHz)	f_{min} (GHz)	f_{max} (GHz)
WM-2540	2540	1270	59.014	75	110
WM-2032	2032	1016	73.767	90	140
WM-1651	1651	825.5	90.790	110	170
WM-1295	1295	647.5	115.75	140	220
WM-1092	1092	546	137.27	170	260
WM-864	864	432	173.49	220	330
WM-710	710	355	211.12	260	400
WM-570	570	285	262.97	330	500
WM-470	470	235	318.93	400	600
WM-380	380	190	394.46	500	750
WM-310	310	155	483.53	600	900
WM-250	250	125	599.58	750	1100
WM-200	200	100	749.48	900	1400
WM-164	164	82	913.99	1100	1700
WM-130	130	65	1153.0	1400	2200
WM-106	106	53	1414.1	1700	2600
WM-86	86	43	1743.0	2200	3300

This scheme, which is based on [6], was produced as follows:

(i) use the existing MIL series [8] as the basis;
(ii) scale widths by dividing by 10;
(iii) express the resulting widths using rounded metric units, i.e. microns.

Minor adjustments have been made to the widths in three bands (but keeping the frequency bands the same) to make the ratios of cut-off frequency values between bands closer to the ideal value of $10^{(1/11)} \approx 1.233$ without appreciably increasing the mismatch when connected to the corresponding waveguides given in [3]. The scheme also uses a suggested upper frequency for the WM-864 band of 330 GHz (rather than 325 GHz), and an associated suggested lower frequency of 330 GHz for the WM-570 band.

In terms of meeting the above design criteria, the frequency bands:

1. Are memorable, i.e. the suggested minimum and maximum frequencies are ten times the values for the MIL frequency bands [8] used for the decade below (with the exception that 325 GHz has been changed to 330 GHz), thus giving full backward compatibility with existing waveguide bands;
2. Link together as two contiguous, interleaved, series: (i) WM-710, WM-470, WM-310, etc; and, (ii) WM-570, WM-380, WM-250, etc;
3. Are extendable to higher frequencies (i.e. smaller waveguide sizes) as follows:
    a. use the waveguide sizes that are unshaded in Table 1;
    b. divide mechanical dimensions by 10;
    c. multiple frequencies by 10;
    d. rename the waveguide accordingly.

    For example, the next two sizes in this series (derived from WM-710 and WM-570) are shown in Table 2;

TABLE II
EXTENDED FREQUENCY BANDS AND WAVEGUIDE DIMENSIONS FOR THE IEEE STANDARD

Name	*a* (μm)	*b* (μm)	f_c (GHz)	f_{min} (GHz)	f_{max} (GHz)
WM-71	71	35.5	2111.2	2600	4000
WM-57	57	28.5	2629.7	3300	5000

4. Are identical with the MIL standard bands [8] in the overlap region, shaded in Table 1, with the exception that 325 GHz has been changed to 330 GHz.

Similarly, the waveguide dimensions (i.e. the widths):

5. Are within 0.05% of MIL standard widths [8] in the overlap region, shaded in Table 1. This produces a worst-case mismatch (i.e. return loss) when connecting to the corresponding MIL standard bands [8] of -70 dB (not including mismatch due to waveguide tolerances);
6. Are within 3% of the widths given in [3]. This produces a worst-case mismatch (i.e. return loss) when connecting to the corresponding bands in [3] of -35 dB (not including mismatch due to waveguide tolerances);
7. Do not use fractional micron values (until the series has been extended to include WM-16.4, i.e. for the frequency range 11 THz to 17 THz!)

Similarly, for the related quantities for all bands:

8. Ratios of minimum to maximum frequency vary between 1.47 and 1.57, indicating that all bands have relatively uniform bandwidths;
9. *k*-factor values are relatively constant, ranging from $1.20 \leq k_1 \leq 1.27$ and $1.83 \leq k_2 \leq 1.91$;
10. Ratios of cut-off frequencies for adjacent bands vary between 1.19 and 1.27 and so are considered similar.

Finally, a new naming convention has been developed for these waveguide bands. Since the sizes are defined in terms of metric units, the letters WM are used to indicate that the size refers to **W**aveguide using **M**etric dimensions. These letters are followed by a number that indicates the size (in microns) of the waveguide broad wall dimension. Table 3 gives a comparison between these new names and the names of related waveguides in the existing MIL standard [8]. Table 4 gives a comparison between the new names and the nearest waveguides given in [3] (i.e. the 'extended MIL' bands).

TABLE III
COMPARISON BETWEEN NEW IEEE AND EXISTING MIL WAVEGUIDE NAMES

MIL name	New IEEE Name	f_{min} (GHz)	f_{max} (GHz)
WR-10	WM-2540	75	110
WR-08	WM-2032	90	140
WR-06	WM-1651	110	170
WR-05	WM-1295	140	220
WR-04	WM-1092	170	260
WR-03	WM-864	220	330

TABLE IV
COMPARISON BETWEEN NEW IEEE AND 'EXTENDED MIL' WAVEGUIDE NAMES

'Extended MIL' name	New IEEE Name	f_{min} (GHz)	f_{max} (GHz)
WR-2.8	WM-710	260	400
WR-2.2	WM-570	330	500
WR-1.9	WM-470	400	600
WR-1.5	WM-380	500	750
WR-1.2	WM-310	600	900
WR-1.0	WM-250	750	1100

This naming convention can easily accommodate 'specialized' (i.e. custom made) waveguide bands, should they be needed, simply by giving the WM letters followed by the broad wall dimension of the custom made waveguide, expressed in microns.

III. FUTURE ACTIVITIES

A. Other waveguide size information

Having chosen a scheme for defining the frequency bands and the waveguide dimensions, this information will be contained in a table in Part 1 of the IEEE standard. It is envisaged that this table will also contain some additional information about each waveguide size. For example, it will be useful to specify tolerances on the critical mechanical dimensions of the waveguide. It has already been discussed within the P1785 Working Group that perhaps two 'grades' of waveguide quality may be given, based on the specified tolerances of the critical dimensions – a 'precision' grade, based on the best achievable tolerances using state-of-the-art manufacturing techniques, and a 'general' grade, that will be realisable using more routine manufacturing techniques.

Other specification parameters for the waveguides are also likely to be given – for example, typical attenuation per unit length, typical mismatch due to waveguide tolerances, etc.

B. Waveguide interfaces

The other main topic that will be covered by this IEEE standard is the definition of suitable interfaces for waveguides used above 110 GHz. It is widely recognised that the popular waveguide interfaces used at millimetre-wave frequencies up to 110 GHz (for example, MIL-DTL-3922/67D [13], also known as UG-387) will not be suitable for use at these higher frequencies. This is because waveguide misalignment, due to tolerances on the critical dimensions of the interfaces, will cause unacceptably large reflections in these smaller waveguide sizes when fitted with such interfaces.

Instead, the suitability of alternative interface designs will be investigated for use with the waveguide sizes specified in the IEEE standard. There are already several interface designs that could be included in the standard. These include:

1. A precision version of UG-387, with tighter tolerances and anti-cocking mechanisms [3]. This could also include additional alignment pins directly above and below the waveguide aperture [1];
2. A miniature flange (the so-called Grammer miniature flange) [3] that has been developed by NRAO for use with the ALMA project[6];
3. A 'plug-and-socket' style of interface [4];
4. A ring-centered flange (see [5] and [7]), of similar dimensions to the UG-387 flange (i.e. with an outer diameter of approximately 19 mm);
5. A miniature ring-centered flange [5], of similar dimensions to the Grammer miniature flange (i.e. with an outer diameter of approximately 12.7 mm).

It is likely that several different types of waveguide interface will be included in the standard so that users can select a suitable design for their particular application (including frequency range).

IV. CONCLUSIONS

This paper has described an on-going activity to develop an international standard for waveguides and their interfaces for use at frequencies of 110 GHz and above. The work to date on defining the frequency bands and waveguide dimensions has been described in detail. It is hoped that potential users of these waveguides will study these proposed frequency bands and waveguide sizes and comment on their suitability for their applications.

The plans for the future development of the standard have also been described. This has included a description of some waveguide interfaces that may be included in the standard. As before, it is hoped that potential users of these interfaces will study these proposed designs and comment on their suitability. Any such comments, either on frequency bands, waveguide sizes or waveguide interfaces, should be sent to: nick.ridler@ieee.org. Comments concerning the proposed frequency bands and waveguide sizes should be sent before May 2010, since this is when the P1785 Working Group will make a decision on whether to accept these proposed frequency bands and waveguide sizes.

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[6] ALMA is the Atacama Large Millimeter / submillimeter Array, www.alma.nrao.edu.

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