Comparison of legacy transmission lines from DC to mmWaves

Point 1: First and foremost what topologies are we considering here out of so many options? Only those which are strongly-established both in academic literature and in the commercial electronics market without an iota of a doubt:

… close metal + dielectric geometry ⟶ coaxial cable operating in TEM mode ⟶ teflon dielectric ($\varepsilon_r = 2.2$, $tan\,\delta = 0.001$) and copper conductors ($\sigma = 58000000$ S/m) ⟶ commercially available dimensions

… open metal + dielectric geometry ⟶ microstrip line operating in $QTEM$ mode ⟶ RT/duroid 5880 substrate ($\varepsilon_r = 2.2$, $tan\,\delta = 0.001$) and copper lines ($\sigma = 58000000$ S/m) ⟶ nomograms from H. A. Wheeler [doi: 10.1109/TMTT.1977.1129179]

… close metal geometry ⟶ rectangular metal waveguides operating in TE_{10} mode ⟶ copper plated inner walls ($\sigma = 58000000$ S/m) ⟶ rectangular waveguide (WR) representative of the US system

…. for a fair comparison of bandwidth (monomode) and group delay, the operation of the transmission lines in their corresponding fundamental modes have been considered here ….

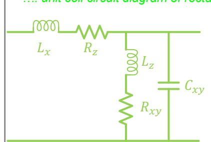
…. for a fair comparison of attenuation (material loss) and impedance, electrical properties of the physical building blocks (zero material dispersion) are made unform for all in the best possible way ….

… okay, so now how do we select the determine the dimensions of their cross-section? For a fair comparison, we go for the options as mentioned above. To the author's judgment, this is probably the most unbiased option ...

Point 2: So from the above discussion in point 1, presented below are the geometrical selections for comparison:

rectangular metal waveguides				
Frequency band designations		Operational frequency (GHz)	Metal waveguide standard	Inner dimensions (mm^2)
		0 – 0.000003	NA	
VLF		0.000003 – 0.00003	NA	
LF		0.00003 – 0.0003	NA	
MF		0.0003 – 0.003	NA	
HF		0.003 – 0.03	NA	
VHF		0.03 – 0.3	NA	
UHF		0.32 – 0.4	WR-2300	584.20 × 292.10
		0.35 – 0.53	WR-2100	533.40 × 266.70
		0.43 – 0.62	WR-1800	457.20 × 288.60
		0.49 – 0.74	WR-1500	381.00 × 190.50
		0.64 – 0.96	WR-1150	292.10 × 146.05
		0.75 – 1.1	WR-1000	253.36 × 126.68
		0.96 – 1.5	WR-700	195.58 × 97.79
		1.12 – 1.7	WR-650	165.10 × 82.55
	R-band	1.7 – 2.6	WR-430	109.22 × 54.61
	D-band	2.2 – 3.3	WR-340	86.36 × 43.18
	S-band	2.6 – 3.95	WR-284	72.13 × 34.03
SHF	E-band	3.3 – 4.9	WR-229	58.16 × 29.21
	G-band	3.95 – 5.85	WR-187	47.54 × 22.14
	F-band	4.9 – 7.05	WR-159	40.38 × 20.19
	C-band	5.85 – 8.2	WR-137	34.84 × 15.79
	H-band	7.05 – 10	WR-112	28.49 × 12.62
	X-band	8.2 – 12.4	WR-90	22.86 × 10.16
	X-Ku-band	10 – 15	WR-75	19.05 × 9.52
	Ku-band	12.4 – 18	WR-62	15.79 × 7.89
	K-band	15 – 22	WR-51	12.95 × 6.47
	K-band	18 – 26.5	WR-42	10.66 × 4.31
	Ka-band	26.5 – 40	WR-28	7.11 × 3.55
EHF	Q-band	33 – 50	WR-22	5.68 × 2.84
	U-band	40 – 60	WR-19	4.77 × 2.38
	V-band	50 – 75	WR-15	3.75 × 1.87
	E-band	60 – 90	WR-12	3.09 × 1.54
	W-band	75 – 110	WR-10	2.54 × 1.27
	F-band	90 – 140	WR-8	2.03 × 1.10
	D-band	110 – 170	WR-6	1.65 × 0.82
	G-band	140 – 220	WR-5	1.29 × 0.64
		170 – 260	WR-4	1.09 × 0.54
		220 – 325	WR-3	0.86 × 0.43

…. unit cell circuit diagram of rectangular metal waveguide operating in TE_{10}-mode



L_x: the transverse magnetic field H_x generates this inductance per unit length,
L_z: the longitudinal magnetic field H_z generates this inductance times unit length,
R_z: the longitudinal current J_z in the walls generates this resistance per unit length,
R_{xy}: the transverse current J_x & J_y in the walls generates this resistance times unit length,
C_{xy}: the transverse electric field E_y generates this capacitance per unit length.

coaxial cables			
Product code	Frequency (GHz)	⌀d (mm)	⌀D (mm)
RG_142_B/U	0 – 6	0.95	2.95
SR_141_M17-QPL	0 – 20	0.92	2.99
MULTIFLEX_141	0 – 33	0.92	2.93
MULTIFLEX_86_HE	0 – 67	0.47	1.48
MULTIFLEX_53-02	0 – 100	0.31	0.99
Not available	0 – 300		

…. these dimensions for diameter of inner conductor (⌀d) and outer conductor (⌀D) have been taken from catalogue of Huber+Shuner for 50 Ω cables with teflon dielectric at different operating frequency regime.

…. finally, coming to microstrip geometry, using the nomogram from H. A. Wheeler on the commercially available substrate RT/duroid 5880, one would require the ratio of width of line to height of substrate to be around 3.11 to achieve 50 Ω characteristic impedance of the line.

….. okay, so with width of microstrip to height of substrate fixed, we explore the possible substrate thickness available from Rogers Corporation which are 0.005", 0.010", 0.020", 0.031", and 0.062" (" means milli-inches and remember that 1 milli-inch is 1/1000 times of an inch which is 2.54 cm). The question is which one to use and how to determine that?

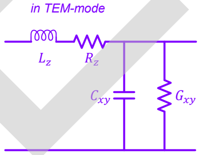
…. at this juncture, it becomes quite dicey and one needs to look beyond theoretical aspects. Here, in context to integrated PCB circuit design, we will consider the effects of surface waves, which is unwanted and increases with substrate thickness and with frequency.

…. note that surface waves, in its fundamental TM_0 mode will always be present due to its DC cut-off frequency irrespective of anything else. But we can at least curb the excitation of the first higher-order surface wave mode TE_1 by appropriately selecting a substrate thickness.

…. in the table below some generic frequency ranges have been determined based on the excitation cut-off of the first high-order surface wave. Note that this is not a standardized protocol, however, has been assumed here for rationality. Otherwise, as required based on other attributes the choice for other substrate height can be exercised.

h (mm)	$f_c(TE_1)$ (GHz)	Frequency range (GHz)
1.575	43.47	0 – 40
0.787	86.99	40 – 80
0.508	134.77	80 – 120
0.252	271.68	120 – 250
0.127	539.09	250 – 300

…. unit cell circuit diagram of coaxial cables and microstrip lines operating in TEM-mode



L_z: Inductance per unit length due to longitudinal conduction current component,
R_z: Ohmic loss per unit length due to longitudinal conduction current component,
C_{xy}: Capacitance per unit length due to transverse electric fields,
G_{xy}: Dielectric loss per unit length due to transverse displacement current.

Point 3: For practical purpose one is interested in group delay variation over frequency which is addressed as effect of dispersion. Theoretically, it is formulated from phase constant as $\tau_g = (\partial\beta/\partial f)^{-1}$. The formulations for phase constant of a microstrip line is cited to E. Yamashita, *et al.*, [doi: 10.1109/TMTT.1979.1129787], while it is purely textbook academics formulations for the coaxial cable and the metal waveguide:

$$\beta_{coax} = Imag\{\gamma\} = Imag\left\{\sqrt{(R + j\omega L)(G + j\omega C)}\right\} =$$

$$Imag\left\{\sqrt{\left(\frac{1}{\pi}\sqrt{\frac{\omega\mu_0}{2}}\left(\frac{1}{d} + \frac{1}{D}\right) + j\omega\frac{\mu_0}{2\pi}ln\left(\frac{D}{d}\right)\right)\left(\frac{2\pi\varepsilon_0\varepsilon_r\omega\,tan\,\delta}{ln(D/d)} + j\omega\frac{2\pi\varepsilon_0\varepsilon_r}{ln(D/d)}\right)}\right\}$$

$$\beta_{mic} = \frac{2\pi f}{c}\sqrt{\varepsilon_{re}} = \frac{2\pi f}{c}\left(\frac{\sqrt{\varepsilon_r} - \sqrt{\varepsilon_{re0}}}{1 + 4F^{-1.5}} + \sqrt{\varepsilon_{re0}}\right)$$

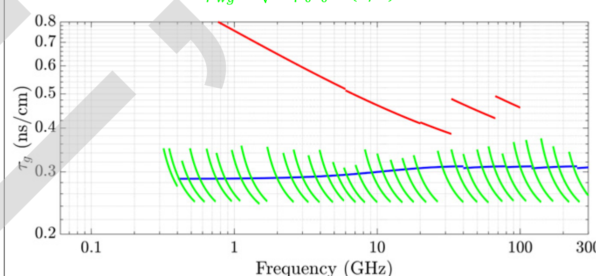
where

$$F = \frac{4hf\sqrt{\varepsilon_r - 1}}{c}\left\{0.5 + \left[1 + 2\,log_{10}\left(1 + \frac{w}{h}\right)\right]^2\right\}$$

and

$$\varepsilon_{re0} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{12h}{w}\right)^{-0.5}$$

$$\beta_{wg} = \sqrt{\omega^2\mu_0\varepsilon_0 - (\pi/a)^2}$$



Point 4: Dispersion (changing τ_g versus f) leads to pulse broadening, and hence inter-symbol interface (ISI) over the waveguide link. The pulse duration, T_b, (separation between two bits) must be longer than group delay over the physical waveguide channel to prevent this mutual overlap at the end of the link. Thus, the maximum channel capacity (C, bits/s) will be limited by the dispersion and the length of the waveguide link (l) and can be expressed as

$$C = \frac{1}{T_b} \leq \frac{1}{(\tau_{g,max} - \tau_{g,min}) \times l}$$

where, $\tau_{g,max}$ and $\tau_{g,min}$ are the the maximum and minimum group delay per unit length, respectively, over the operational bandwidth.

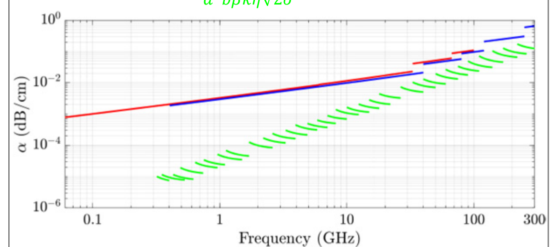
…. note that for any practical link design, the operational bandwidth will be limited by a lot of constraints like attenuation, input and output impedance matching, sensitivity of the system, noise floor, etc.

Point 5: The formulations for loss as attenuation per unit length follows (here the symbols have their usual meanings as designated in any electromagnetics and microwave engineering textbook):

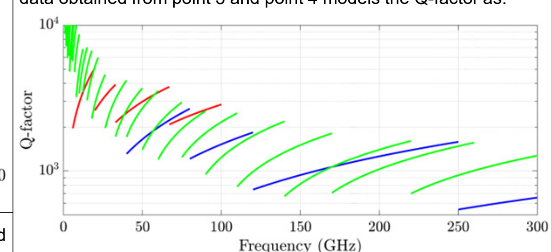
$$\alpha_{coax} = \frac{\pi f}{c_0}\sqrt{\varepsilon_r}\,tan\,\delta + \frac{1}{2\pi Z_0}\left(\frac{1}{d} + \frac{1}{D}\right) \times \sqrt{\frac{\mu\omega}{2\sigma}}$$

$$\alpha_{mic} = \frac{k_0\varepsilon_r(\varepsilon_{re} - 1)\,tan\,\delta}{2\sqrt{\varepsilon_{re}}(\varepsilon_r - 1)} + \frac{\sqrt{\omega\mu_0}}{Z_0 w\sqrt{2\sigma}}$$

$$\alpha_{wg} = \frac{\sqrt{\omega\mu_0}}{a^3 b\beta k\eta\sqrt{2\sigma}}(2b\pi^2 + a^3k^2)$$



Point 6: One very important property without which the discussion on transmission line will never be complete is its quality-factor (Q-factor), which can be estimated analytically as $Q = \beta \times (2\alpha)^{-1}$. The data obtained from point 3 and point 4 models the Q-factor as:



Point 7: Talking as conclusion

…. In terms of power loss and information loss over propagation in the transmission lines, metal waveguides and microstrip lines provides the best performance, respectively.

…. It is scholarly and aspiring to do such comparisons, but on a practical sense one can never replace one transmission line with the other just because of some performance gap.

…. This is because of other aspects that are not discussed here which includes power handing capacity, cost, system assembly, form factor, electronic packaging, ... those that are difficult to be justified by a theoretical model.