A.1) The Rowland circle

A.1.1) Theoretical background

The Rowland circle is a concave grating arrangement that can be used in the realisation of a grating spectrograph. In a grating spectrograph, coloured images of a slit source are produced in the various orders into which the grating separates the incident light [1]. A simple spectrograph is presented in figure A.1

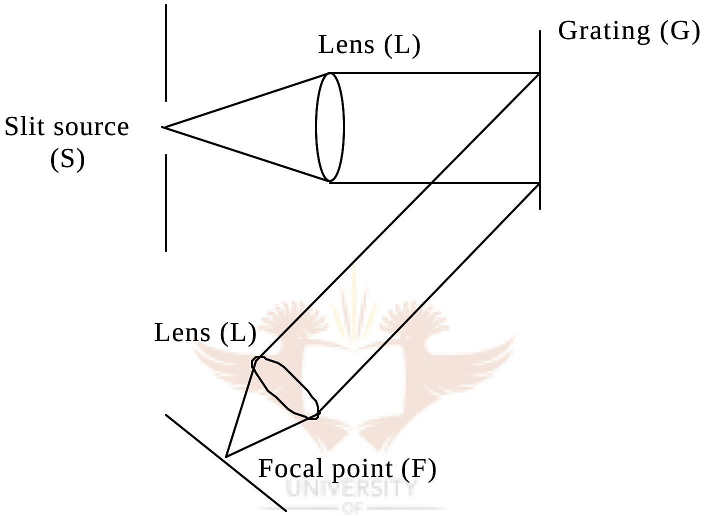


Figure A.1: A grating spectrometer

The Rowland circle limits the loss of light that necessarily arises when diffracted rays are focused by means of lenses [1]. The Rowland circle identifies the correct locations of the entrance slit (P_0) and the exit slit (P’). If P_0 is anywhere on the circle whose diameter is equal to R, the radius of curvature of the grating, and *which contacts the centre of the grating at O* as shown in figure A.2, then the specular beam and the dispersed beams in all orders will be focused at other points on the same circle.

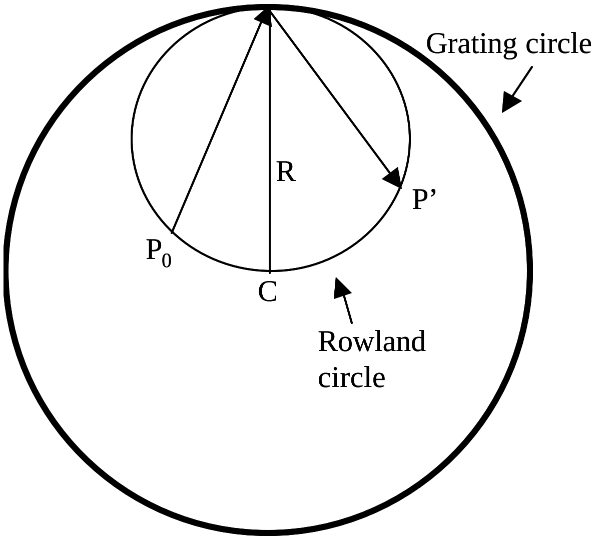


Figure A.2: Rowland circle geometry

To prove this, we will show that that P_0 and P’ satisfy the grating equation if they lie on the Rowland circle. We start by considering figure A.3, where the reflection point is in the middle of the grating. The coordinate origin is defined at O(0,0), so that $P_0(x_0,z_0)$ and P’(x’,z’) are identified by

$$x_0 = -r\sin\theta \qquad z_0 = r\cos\theta \tag{A.1}$$

$$x' = r'\sin\theta' \qquad z' = r'\cos\theta'$$

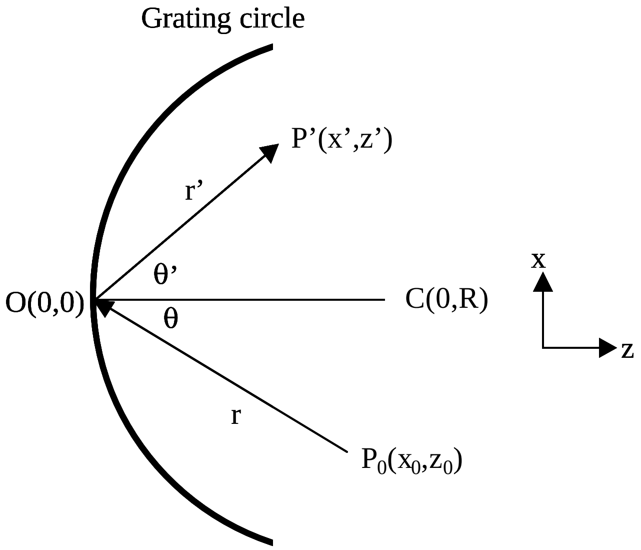


Figure A.3: Concave geometry for O at the centre of the grating

Next we consider a different position of reflection on the grating circle, namely P(x,z), as in figure A.4. Note that the angles *q* and *q'* are still being referenced to the line connecting C and the point of reflection on the grating.

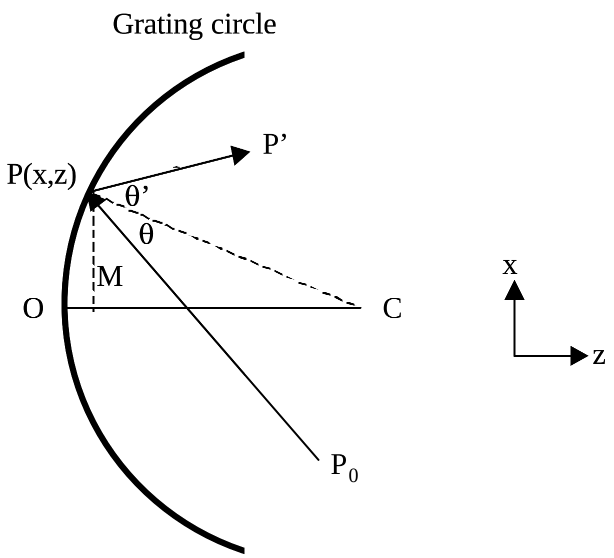


Figure A.4: Reflection point P not in the middle of the grating

The arc OP is required to contain an integral number of grooves that is approximately *x/a*, where *a* is the groove spacing (assuming that the arc length is small compared to R). If P' is to be at an interference maximum, then each groove contributes a beam whose optical path length as measured from P_0 differs from contributions due to adjacent grooves by a factor *m l* (for dispersion into the order *m*). The total optical path length difference between contributions from O an P is

$$\overline{P_0OP'} - \overline{P_0PP'} = \frac{m l x}{a} \qquad \text{(A.2)}$$

where

$$\overline{P_0OP'} = r + r' \qquad \text{(A.3)}$$

and

$$\overline{P_0PP'} = \left[(x_0 - x)^2 + (z_0 - z)^2\right]^{1/2} + \left[(x' - x)^2 + (z' - z)^2\right]^{1/2} \qquad \text{(A.4)}$$

As the dimension of z is very small compared to the other dimensions in figure A.4, we can ignore the terms of z^2 when expanding equation A.4, so that we have the approximation

$$\overline{P_0PP'} \approx \left[x_0^2 + z_0^2 - 2\left(xx_0 + zz_0\right) + x^2\right]^{1/2} + \left[x'^2 + z'^2 - 2\left(xx' - zz'\right)^2 + x^2\right]^{1/2} \tag{A.5}$$

Equation A.5 can be simplified even further by using a standard approximation to the curvature of a spherical surface as given in [2] as

$$z \approx \frac{x^2}{2R} \tag{A.6}$$

By substituting equations A.1 and A.6 into equation A.5 leads to

$$\begin{aligned} \overline{P_0PP'} \approx & \left\{r^2 - 2\left[x\left(-r\sin q\right) + \frac{x^2}{2R}\left(r\cos q\right)\right] + x^2\right\}^{1/2} \\ & + \left\{r'^2 - 2\left[x\left(-r'\sin q'\right) + \frac{x'^2}{2R}\left(r'\cos q'\right)\right] + x^2\right\}^{1/2} \\ \therefore \overline{P_0PP'} \approx & \; r\left\{1 + \frac{2x\sin q}{r} - \frac{x^2\cos q}{rR} + \frac{x^2}{r^2}\right\}^{1/2} + r'\left\{1 + \frac{2x\sin q'}{r'} - \frac{x'^2\cos q'}{r'R} + \frac{x^2}{r'^2}\right\}^{1/2} \end{aligned} \tag{A.7}$$

We now use the fact that *x/r* and *x/r'* are small (in the designs presented in chapter 7.5, r and r' are in the order of 16500µm whereas the x's are in the order of 200µm) to simplify the square root operation. Because $(1+p)^{1/2}$ » $1 + p/2 - p^2/8 + \ldots$, we can state for our case that, for the leftmost term in equation A.7 for example

$$p = \left(\frac{x}{r}\right)^2 + \frac{2x\sin q}{r} - \frac{x^2\cos q}{Rr} \tag{A.8}$$

By expanding the leftmost term of equation A.7, we can approximate it by

$$\overline{P_0P} \approx r\left\{1+\frac{x^2}{2r^2}+\frac{x\sin q}{r}-\frac{x^2\cos q}{2Rr}-\frac{x^2\sin^2 q}{2r^2}\right\} \tag{A.9}$$

$$\approx r + x\sin q + \frac{x^2}{2r}\cos^2 q - \frac{x^2\cos q}{2R}$$

If only the terms of second or lower order in x are retained and x/r is assumed small. Similar steps for the rightmost term of equation A.7 leads to the approximation

$$\overline{P_0PP'} \approx (r+r') + x(\sin q - \sin q') + \frac{x^2}{2}\left[\left(\frac{\cos^2 q}{r}-\frac{\cos q}{R}\right)+\left(\frac{\cos^2 q'}{r'}-\frac{\cos q'}{R}\right)\right] \tag{A.10}$$

Equation A.10 can now be substituted in equation A.2 (which expresses the conditions for an interference maximum at P' given the source at P_0):

$$\overline{P_0OP'} - \overline{P_0PP'} \approx x(\sin q' - \sin q) + \frac{x^2}{2}\left[\left(\frac{\cos^2 q}{r}-\frac{\cos q}{R}\right)+\left(\frac{\cos^2 q'}{r}-\frac{\cos q'}{R}\right)\right] = \frac{m l x}{a} \tag{A.11}$$

The first term on the left of equation A.11 is the familiar form of the grating equation, while the second term will be zero (at this level of approximation) provided that

$$r = R\cos q \tag{A.12}$$

and

$$r' = R\cos q' \tag{A.13}$$

Equations A.12 and A.13 imply that OP_0C and OP'C define right triangles, and because $\overline{OC}$ is common to both triangles, points P_0 and P' must lie on a common circle whose diameter is $\overline{OC}$, namely the Rowland circle.

We recognise that P' is the image of P_0 in order *m* and wavelength λ, because all paths P_0PP' are equivalent within an integral number of wavelengths. Thus the contributions at P' that originate at P_0 are all in phase provided that the angles *q* and *q*' satisfy $a(\sin q' - \sin q) = m l$.

This constraint is the basis used in the determination of the geometry for the designs in chapter 7.

A.1.2) Use of the Rowland circle in arrayed waveguide gratings

Rowland circle configurations are used in the geometrical setup of planar lightwave circuit (PLC) arrayed waveguide gratings (AWGs), as AWGs can essentially be viewed as spectrometers. The use of Rowland circles in AWGs differs from figure A.2 in that a *reflective* grating is not employed. Instead, two Rowland geometries are employed, each in a separate star coupler. In the first star coupler, a diffraction of light is obtained in the slab waveguide, analogous to the incident light from point P_0 to the grating in figure A.2. A Fraunhofer diffraction pattern (Fourier transform of the input light) is obtained at the slab/array interface [3]. The array of waveguides act as the grating, with the waveguide lengths chosen such that the optical path length difference between adjacent waveguides are integer multiples of the centre design wavelength. The star couplers in the AWG are placed back to back, resulting in the second star coupler acting as the imaging stage as set out in figure A.2, where the light propagates from the grating to point P'.

A.1.3) References

1) M. Born, E. Wolf, "Principles of optics", Pergamon Press, 6th edition, pp. 412 – 413.
2) M. Klein, T. Furtak, "Optics", John Wiley and Sons, pp. 314 – 317, 1986.
3) K. Okamoto, H. Takahashi, S. Suzuki, A. Sugita, Y. Ohmori, "Design and fabrication of integrated optic 8 × 8 star coupler", Electronics Letters, vol. 27, pp. 774 – 775, 1991.

A.2) Star coupler simulation program

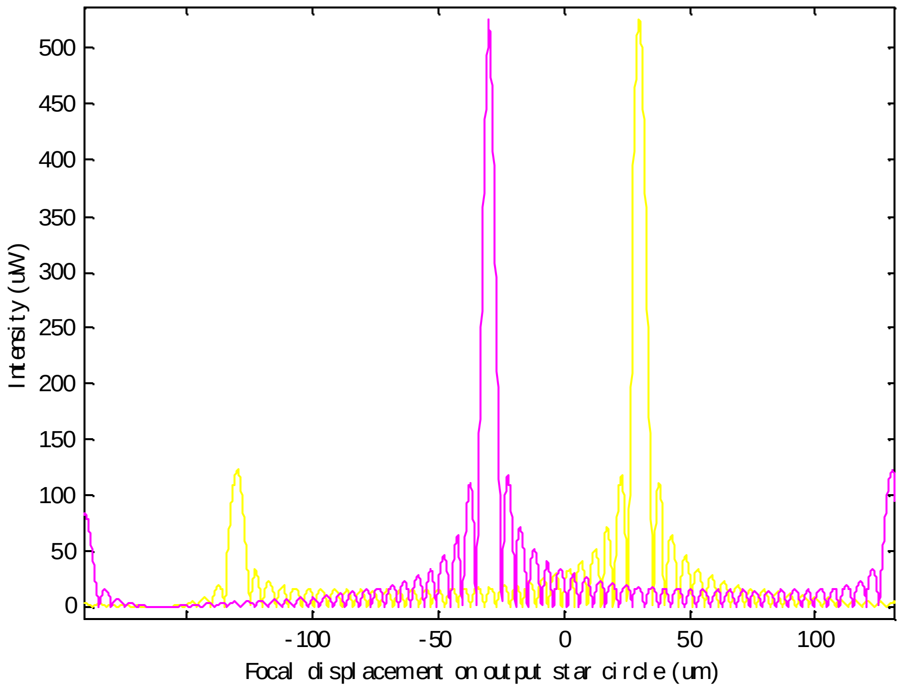


Figure A.1: Example output of program A.2. The M-1, M and M+1 orders as discussed in section 7.5 are clearly visible

A.2) Arc length generation program

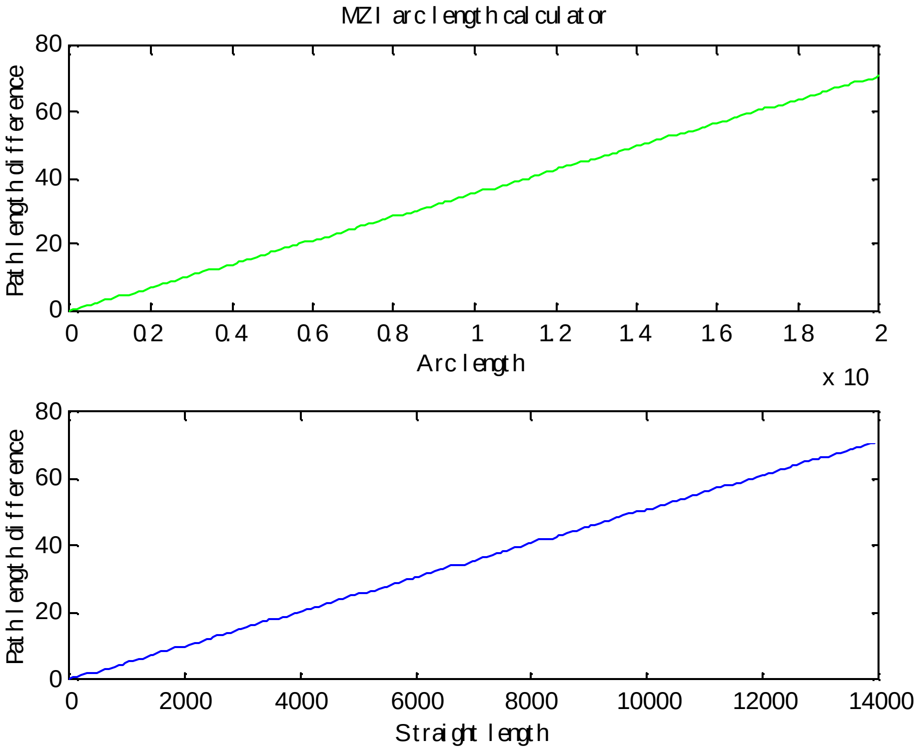
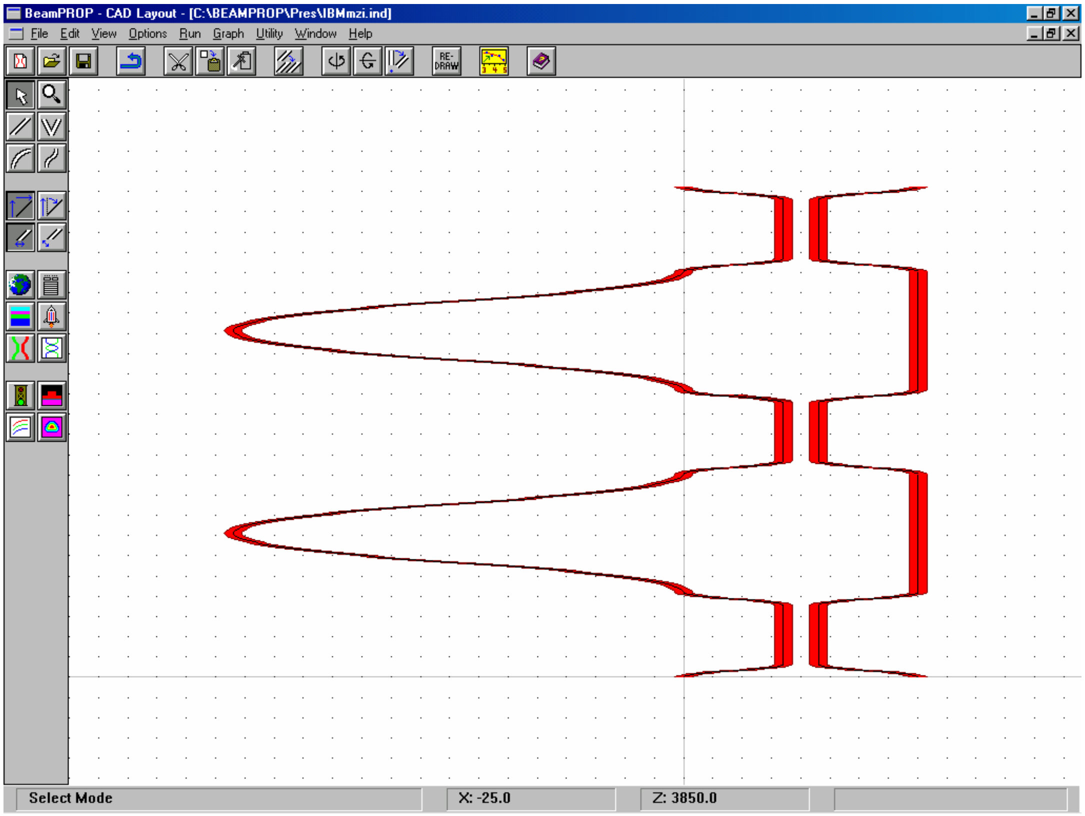


Figure A.2: Example output of arc length program

A.3) Full layout of MZI lattice filter



Select Mode

X: -25.0

Z: 3850.0

Figure A.3: Example of MZI lattice filter layout in BeamPROP

A.4) Internet reference: Chapter 1 [5]

Once-Bright Future of Optical Fiber Dims

By SIMON ROMERO

n the last two years, 100 million miles of optical fiber - more than enough to reach the sun - were laid around the world as companies spent $35 billion to build Internet-inspired communications networks. But after a string of corporate bankruptcies, fears are spreading that it will be many years before these grandiose systems are ever fully used.

There is a glut of capacity of high-speed, long-haul information pipelines, but a shortage of the high-speed, local-access connections that consumers and businesses need to gain access to the Web. It is as if superhighways stand nearly empty while traffic backs up at the Holland and Lincoln tunnels.

Few people have fast Internet connections, and prices are rising for those who do. Computer users with common dial-up Internet connections find their Web browsers stalled, and people trying to make regular phone calls complain increasingly of busy signals.

Meanwhile, investment in the communications industry, especially in fiber optic networks, has sharply declined, leaving companies with fiber that may never be "lit," as commercially available wire is called. Only 5 percent of fiber in the ground is on, and lighting fiber can cost large corporate clients about $500 million and 15 months, according to Salomon Smith Barney.

"There may be a significant amount of dark fiber in the ground, but it takes a lot more money to light fiber than to lay it and even more to deliver it to the end user," Howard E. Janzen, head of Williams Communications, said in a recent interview. "The challenges will force the flakes to drop out."

The industry bubble has had an impact on the rest of the economy, too. Billions invested in telecommunications companies now appear to have been wasted. The drying up of capital investment is one reason that the economy has slowed sharply, and some economists argue that while the Federal Reserve's efforts to lower interest rates will stimulate some parts of the economy, it may be years before growth returns to the areas that were so hot only a year ago.

The pain is spreading to many companies, their investors, their creditors and their workers.

On Friday, Nortel Networks of Canada said it would lose an astonishing $19 billion this quarter because its phone equipment sales were falling. And 360networks, also of Canada, failed to make an interest payment on Friday, raising concern that the developer of a huge fiber optic network could seek bankruptcy protection or default on its debt.

The buildup of networks was expected to usher in a prosperous era of vast new commercial applications for the Internet, fed by soaring supplies of bandwidth, the range of frequencies used to transmit communications signals.

Some entrepreneurs were so optimistic that they suggested sending high-altitude aircraft to circle above big cities, beaming signals down to consumers. Today, only about 10 percent of American homes have high- speed access to the Internet, through conventional cable networks and digital subscriber lines.

In Europe, anxieties run high for different reasons. Companies spent large sums there to acquire licenses to provide advanced wireless services. Deutsche Telekom, British Telecom and other companies are now seeking to renegotiate their agreements to pay $125 billion for these licenses. To reduce overwhelming debts, some companies are trying to sell assets and agreeing to share some network costs.

Back in the United States, the stakes are perhaps highest for the companies that built transcontinental and trans oceanic fiber optic networks capable of carrying huge amounts of voice and data traffic.

The problems are similar to those in the railroad industry after the Civil War, when an economic boom fueled speculation by financiers.

"In the railroad age, speculators built rail lines but often left it up to the locals in town to build the roads to each station," said Brian Kinard, a venture capitalist in San Francisco who focuses on communications companies. "Today, it's the responsibility of the capital markets to fund construction of all parts of the network. And suddenly, it's not clear whether investors will continue to do so."

By the early 1870's an abundance of cheap financing, rather than business fundamentals, led to a doubling of railroad mileage from the previous decade. Then, in 1873, the collapse of the Northern Pacific Railroad ruined its principal owner, the Philadelphia banking firm Jay Cooke & Company, leading to a market crash.

In the following years, two-fifths of railroad bonds went into default, and railroad miles built fell by 80 percent. It was not until the end of the 1870's that investment began to resurface. Still, railroads, the leading technology of their day, were never again seen in the same light.

Similar clouds may be gathering over the telecommunications industry. So far this year, companies have defaulted on $13.9 billion of telecommunications bonds, resulting in investor losses of $12.8 billion, according to Fitch IBCA Duff & Phelps, a debt-rating company. For all of last year, investor losses amounted to $5.2 billion on such bonds. Companies as large and influential as GE Capital, the financial arm of General Electric, are said to be exposed to substantial losses by their roles in the financing of telecom and related companies. And investors in the companies' stocks have seen their value plunge.

In the 1980's companies began laying fiber optic cable, sometimes alongside rail lines. But the value of the long-haul networks, or backbone, over which Internet data could travel soared in 1996 when WorldCom acquired MFS Communications, a fiber optic network, for $14 billion.

Newcomers were also emboldened by the Telecommunications Act of 1996, which helped to deregulate the communications industry. The stage was set for a company called Global Crossing.

The brainchild of Gary Winnick, a banker and former successful Wall Street sales executive under the tutelage of Michael R. Milken, Global Crossing was formed in Beverly Hills in 1997 with the goal of building a fiber optic networklinking the Americas with Asia and Europe.

After Mr. Winnick, without much strenuous effort, secured $750 million and laid a fiber optic cable across the Atlantic Ocean, Global Crossing went public.

The company's shares soon hit a high of $73.375, valuing Global Crossing at nearly $30 billion. That was many times what its network had cost, and encouraged similar ventures, like 360networks and Level 3 Communications. (Global Crossing shares closed at $8.66 on Friday.)

Financiers feverishly raced to provide the post-cold war economy with communications capacity, much the same way financiers backed railroads seeking to increase transportation after the Civil War.

New competitors joined the fray. Cincinnati Bell, a local phone company, acquired a fiber optic network operator and was reborn as Broad wing. The Williams Companies, a Tulsa, Okla.-based gas-pipeline operator, formed Williams Communications, which built a national fiber optic network partly by laying fiber along its parent company's pipelines.

"Build it and they will come," became the mantra of billionaire fiber barons. Venture capitalists began financing companies with plans to deliver data quickly to computer users in other ways, like using satellites and even high-altitude aircraft.

The optimism peaked last July when JDS Uniphase, a little-known Canadian maker of laser filters used to light fiber, announced a plan to acquire SDL, a little-known competitor, for stock then worth $41 billion and now valued less than $6 billion. It was the biggest merger in the history of the technology industry.

Then concern began to build about market valuations. At about the same time, technology ventures began to have trouble securing financing. The share prices of many communications companies plunged.

The swelling supply of fiber led to a decline in prices of bandwidth, which is increasingly traded like barrels of oil or pork bellies. Prices could fall 60 percent this year, on top of similar declines last year, according to estimates by Morgan Stanley Dean Witter.

The IDT Corporation, an international phone company based in New Jersey, says a 10-year contract for a phone line that can carry nearly 600 conversations has fallen to $1.8 million, from $12 million in 1999. Competition has led to even steeper declines for lines that can carry four times as much traffic. Carriers say that any glut is temporary, and that measurements of supply should not include dark fiber. Moreover, Internet use and the demand for bandwidth continue to climb.

While carriers bet on a recovery in bandwidth prices, problems have arisen in other parts of the communications industry.

One-time titans in communications equipment, like Lucent Technologies and Nortel, have reported giant losses as sales have declined. Some of the credit extended by these companies to clients to buy equipment is at risk of default, making it riskier for banks to lend money to even the biggest equipment companies. More than 100,000 jobs have been eliminated from the communications industry since last year.

NorthPoint Communications, a provider of fast Internet access, shut down in March, leaving more than 100,000 customers scrambling to find new service. Several similar but smaller high-speed Internet companies have also closed. Others are teetering.

The ranks of bankrupt telecommunications companies include Winstar, whose corporate trophy, a 200- foot blimp that still flies above New York, seems little more than an eerie relic of the late 20th-century telecommunications boom. Winstar paid for the blimp last year when the outlook for the telecommunications industry was still bright.

http://www.nytimes.com/2001/06/18/technology/18MELT.html?ex=993857101&ei=1&en=ee5126d6ad15b6c8